Techniques to Enhance the Lifetime of Mobile Ad Hoc Networks

Niranjan Kumar Ray

Department of Computer Science and Engineering
National Institute of Technology Rourkela
Rourkela, Odisha 769 008, India

Techniques to Enhance the Lifetime of Mobile Ad Hoc Networks

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Niranjan Kumar Ray
(Roll: 508CS302)

under the guidance of

Dr. Ashok Kumar Turuk

Department of Computer Science and Engineering
National Institute of Technology Rourkela
Rourkela, Odisha 769 008, India

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Department of Computer Science and Engineering
National Institute of Technology Rourkela
Rourkela-769 008, Odisha, India.

Certificate

This is to certify that the thesis entitled **Techniques to Enhance the Lifetime of Mobile Ad Hoc Networks**, submitted by **Niranjan Kumar Ray**, Research Scholar, in the *Department of Computer Science and Engineering*, *National Institute of Technology*, *Rourkela*, *India*, for the award of the degree of **Doctor of Philosophy**, is a record of an original research work carried out by him under my supervision and guidance. The thesis fulfills all requirements as per the regulations of this Institute and in my opinion has reached the standard needed for submission. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

Ashok Kumar Turuk

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Abstract

Devices in Mobile Ad Hoc Networks (MANETs) are mostly powered by battery. Since the battery capacity is fixed, some techniques to save energy at the device level or at the protocol stack should be applied to enhance the MANETs lifetime. In this thesis, we have proposed a few energy saving approaches at the network layer, and MAC layer.

First, we proposed a routing technique, to which the following metrics are built into: (*i*) node lifetime, (*ii*) maximum limit on the number of connections to a destination, and (*iii*) variable transmission power. In this technique, we consider a new cost metric which takes into account the residual battery power and energy consumption rate in computing the lifetime of a node. To minimize the overutilization of a node, an upper bound is set on the number of connections that can be established to a destination. The proposed technique is compared with AODV [1] and LER [2]. It outperforms AODV and LER in terms of network lifetime.

Next, a technique called *Location Based Topology Control with Sleep Scheduling* (LBTC) is proposed. It uses the feature of both topology control approach in which the transmission power of a node is reduced, and power management approach in which nodes are put to sleep state. In LBTC the transmission power of a node is determined from the neighborhood location information. A node goes to sleep state only when: (*i*) it has no traffic to participate, and (*ii*) its absence does not create a local partition. LBTC is compared with LFTC [3] and ANTC [4]. We observed that the network lifetime in LBTC is substantially enhanced.

A framework for post-disaster communication using wireless ad hoc networks is proposed. This framework includes: (*i*) a multi-channel MAC protocol, (*ii*) a node-disjoint multipath routing, and (*iii*) a distributed topology aware scheme. Multi-channel MAC protocol minimizes the congestion in the network by transmitting data through multiple channels. Multipath routing overcomes the higher energy depletion rate at nodes associated with shortest path routing. Topology aware scheme minimizes the maximum power used at node level. Above proposals, taken together intend to increase the network throughput, reduce the end-to-end delay, and enhance the network lifetime of an ad hoc network deployed for disaster response.

Dissemination of Work

Journals

1. **Niranjan K. Ray** and Ashok K. Turuk, A Technique to Improve Network Lifetime in Mobile Ad Hoc Networks, *International Journal of Communication Systems* (Wiley), DOI: 10.1002/dac.2784, 2014.

2. **Niranjan K. Ray** and Ashok K. Turuk, Performance Evaluation of Different Wireless Ad Hoc Routing Protocols, *International Journal of Wireless and Mobile Networks*, vol. 4(2), pp. 203 - 216, 2012.

3. **Niranjan K. Ray**, Harsh B. Sharma and Ashok K. Turuk, Network Lifetime Analysis of AODV, DSR and ZRP at Different Network Parameters, *International Journal of Mobile Network Communications & Telematics*, vol. 2(3), pp. 37 - 48, 2012.

4. **Niranjan K. Ray** and Ashok K. Turuk, LBTC: A Conceptual Energy Saving Framework for Mobile Ad hoc Networks, *Research Journal of Information Technology*, vol. 4(4), pp. 166 - 175, 2012.

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6. **Niranjan K. Ray** and Ashok K. Turuk, A Framework for Post-Disaster Communication using Wireless Ad Hoc Networks, Communicated to *Wireless Personal Communications.* (Springer).

Conference Proceedings

1. **Niranjan K. Ray** and Ashok K. Turuk, A Review on Energy Efficient MAC Protocols for Wireless LANs, In *Proceedings of* 4^{th} *IEEE International Conference on Industrial and Information Systems*, Srilanka, pp. 137 - 142, 2009.

2. **Niranjan K. Ray** and Ashok K. Turuk, A Energy Efficient Techniques for Wireless Ad Hoc Network, In *Proceedings of International Joint Conference on Information and Communication Technology (IJICT)*, pp. 105 - 111, 2010.

3. **Niranjan K. Ray** and Ashok K. Turuk, Analysis of Topology Control Algorithms in Ad Hoc and Sensor Networks, In *Proceedings of International Conference on Challenges and Applications of Mathematics in Science and Technology (CAMIST)*, pp. 562 - 571, 2010.

4. **Niranjan K. Ray** and Ashok K. Turuk, A Framework for Disaster Management using Wireless Ad Hoc Networks, In *Proceedings of International Conference on Communication, Computing & Security (ICCCS)*, pp. 138 - 141, 2011.

Book Chapters

1. **Niranjan K. Ray** and Ashok K. Turuk, Energy Conservation Issues and Challenges in MANETs, *Chapter 17: Technological Advancements and Applications in Mobile Ad hoc Networks: Research Trends*, IGI Global publisher, USA, pp. 291 - 318, 2012.

2. **Niranjan K. Ray** and Ashok K. Turuk, Broadcasting in Wireless Ad hoc Networks: Approaches and Challenges, *Chapter 4: Technological Advancements and Applications in Mobile Ad hoc Networks: Research Trends*, IGI Global publisher, USA, pp. 65 - 80, 2012.

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Acronyms

ACK	Acknowledgment
AODV	Ad Hoc On-demand Distance Vector
ARPANET	Advance Research Project Agency Network
ATIM	Ad Hoc Traffic Indication Message
BI	Beacon Interval
CBR	Constant Bit Rate
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
DARPA	Defense Advanced Research Project Agency
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
NACK	Negative Acknowledgment
RREQ	Route Request
RREP	Route Reply
RSSI	Received Signal Strength Indicator
RTS	Request to Send

Chapter 1

Introduction

Wireless technology has been influencing the society in many ways. Today a wide range of wireless products are available in the market. Moreover, devices are getting more and more mobile. Wireless technology has various applications which includes cellular data services (GSM, GPRS, CDMA, and 3G), Wireless-Fidelity (IEEE 802.11), Bluetooth (IEEE 802.15.1), Zigbee (IEEE 802.15.4), WiMax (IEEE 802.16), Ultra Wide Band (IEEE 802.15.3), etc. These technologies are available on an ever increasing number of devices such as laptops, mobile phones, PDA, *etc.*, which allows them to connect different networks. Explosive growth of wireless communication networks has made this as one of the important areas of research. Most of the wireless networks are infrastructure dependent and requires a base station or access point to operate. For example, cellular networks such as GSM and CDMA requires a base station for communication among the mobile devices. There also exists another type of wireless networks called ad hoc networks which operates without the support of any pre-established fixed infrastructure. They can be deployed anywhere at anytime with minimal administration, and are self-organized, self-controlled, self-configurable network [5–9].

1.1 Wireless Ad Hoc Networks

The concept of wireless ad hoc networks is nearly three decades old. In 1980 Defense Advanced Research Projects Agency (DARPA) [10] started a Packet Radio Network (PRNET) project. This project was primarily intended for military application. Later, it was extended to multi-hop networks. PRNET was a centralized system based on ALOHA and CSMA. A few years latter DARPA started a project called Survival Radio Networks (SURAN). The objective of the project was to provide ad hoc networking using low-power, low cost and smaller size devices. The project also emphasized on developing efficient protocols, improving network scalability and survivability. Today's wireless ad hoc network is based on PRNET and SURAN.

Wireless ad hoc network is a collection of nodes. A node in a ad hoc network act like a host as well as a router. Nodes move randomly and organize themselves arbitrarily. As a result the network topology changes rapidly and unpredictably. Communication among nodes can be point-to-point or multi-hop. Point-to-point communication is possible when they are within the radio range of each other. However, in multi-hop communication a packet reaches the destination through multiple number of intermediate nodes, in this case they act as relay nodes. These relay nodes, transmit their own traffic, as well as traffic from other nodes. Wireless ad hoc networks have a variety of applications such as in military applications, emergency operation, environmental monitoring, patient monitoring, etc. The major difference between a cellular network and a wireless ad hoc network lies in the resource management and routing. A base station in a cellular network simplifies the routing activity; routing decisions are taken in a centralized manner at the base station. But in a wireless ad hoc network routing decisions are made in a distributed manner at the node level. Design of routing protocols in wireless ad hoc networks is a challenging task due to multi-hop communication, node mobility, limited bandwidth and constrained battery power. Realizing the importance of open standards in wireless ad hoc network, a working group termed as Mobile Ad Hoc Networks (MANET) within the Internet Engineering Task Force (IETF) [11] was formed in the year 1997 to standardize the protocols and functional specification. The creation of MANET working group stimulated intense research activity in wireless ad hoc networking.

1.2 Issues and Challenges in MANETs

We have listed below a few issues and challenges in MANETs:

- Unpredictable mobility
- Low bandwidth channels
- Clock synchronization
- Multi-hop routing
- Quality of service

- Energy efficiency
- Scalability, security & many more

Designing an efficient MAC protocol with built-in collision avoidance mechanism is a challenging task. A collision avoidance scheme using omni-directional antennas waste a large portion of the network capacity by reserving the medium over a large area. The medium utilization can be improved by controlling the sender transmission power. Adaptive power control mechanism introduces additional overhead in the process of route discovery and topology maintenance in ad hoc networks. Some of the major issues at MAC layer are listed below:

- Fairness: A MAC protocol should provide equal share of bandwidth to all competing nodes. Fairness can be flow-based or node-based. The flow-based provides an equal share for competing data transfer sessions. While node-based provides an equal share for competing nodes. In MANETs fairness is important due to multi-hop relaying.

- Distributed operation: MANET operates in an environment where centralized coordination is not desirable. Therefore, MAC protocol should be distributed and have minimum control overhead.

- Interference: Wireless medium is error prone. To access the channel, contention among the nodes takes place. This increases interference in the network.

- Hidden and exposed terminals: Hidden nodes are those nodes, which are not present within the transmission range of the sender but with the receiver. Exposed nodes are those nodes, which are present within the transmission range of the sender. Transmission from hidden nodes interfere with the on-going transmission, while the exposed nodes are prohibited for the duration of transmission. To increase the channel utilization, and network throughput, hidden and/or exposed nodes should actively participate without interfering with the on-going transmission.

Some of the challenges which are specific to routing in MANETs are discussed below:

- Dynamic topology: Since nodes are mobile in MANET, the network topology and connectivity among the nodes changes rapidly and unpredictably. This may lead to frequent path break.

- Bandwidth constraint: Wireless medium is bandwidth constrained. The bandwidth availability per wireless link depends on the number of nodes and the traffic they handle. Therefore, only a fraction of the total bandwidth is available to each node. Control packets are flooded in the network, in order to established a path between the source-destination pair.

- Control overhead: This consumes the precious available bandwidth.

- Loop-free routing: This is a basic requirement for routing protocol to avoid unnecessary wastage of network bandwidth. Transient loops may be formed in ad hoc network due to the unpredictable node movement. Thus, routing protocol should take corrective measures to detect and eliminate transient routing loops.

While designing a routing protocol for MANET, care should be taken to address the above mentioned issues.

Some of the issues such as quality of service (QoS), energy conservation, security can be addressed at different layers of the protocol stack. MANET protocol stack where energy management can be addressed is shown in Figure 1.1.

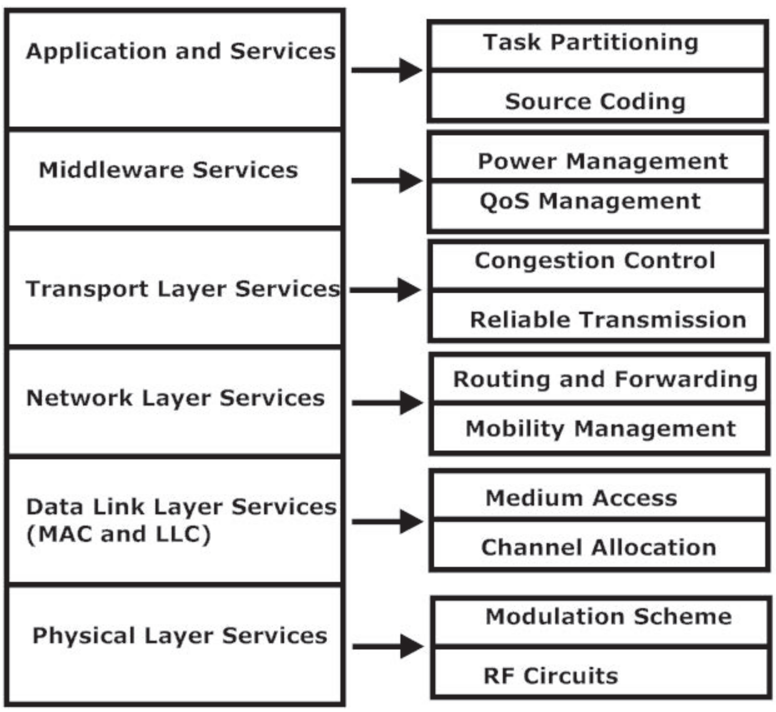


Figure 1.1: MANET protocol stack.

1.3 Energy Management

Several energy management schemes have been implemented successfully for infrastructure based wireless network [12–14]. In such networks a centralized entity called base station manages the energy for mobile devices. These devices are put to dose state when they have no traffic to participate. During this period, base station buffers the packet intended for a device, and delivers it when the device wakes up. However, this strategy cannot be applied to MANET as there is no centralized authority similar to base station. A node that stays most of the time in doze state may save substantial amount of energy but can adversely affect the network connectivity. Therefore, the goal of energy management in MANET is not only to maximize the network lifetime but also to maintain the network connectivity.

Energy conservation can be performed at different layers of the MANET protocol stack. Different techniques have been proposed to achieve energy efficiency. For the power management, authors have emphasized on the following:
(*i*) Battery management: A significant amount of energy can be saved, varying the discharge pattern of battery,
(*ii*) Designing low power devices: Low power wireless interface has the potential to save significant energy,
(*iii*) Developing energy aware MAC protocol,
(*iv*) Designing energy aware routing protocol, and
(*v*) Minimizing interference and congestion in the network.

Therefore, MANET protocols should choose a path that balances between the energy consumption of all the nodes and the network lifetime. It is also important to maintain a trade off between energy consumptions and other metrics, such as: throughput, end-to-end delay, link reliability, network capacity, etc. Research have been made on exclusive layers of the protocol stack as well as on cross layer optimization to conserve energy [6, 7, 15–18].

The term power and energy are often used interchangeably by the authors. In this thesis, we have also used the two terms *power* and *energy* interchangeably.

1.4 Motivation of the Work

Nodes in MANETs are powered by battery. Therefore, their lifespan depends on the battery capacity, which is limited in nature. Longevity of MANET is crucial in certain applications such as in battlefield, disaster monitoring, etc. If a node runs out of battery, it adversely affect the network performance. To enhance the network lifetime, available battery capacity must be used judiciously.

Routing protocols based on hop count metrics are not energy efficient [19–21]. Moreover, hop count metric is not sufficient enough to determine the quality and stability of a path in many environments. Nodes on a minimum hop path, will deplete their battery power at a higher rate, (as the traffic will follow the minimum hop path) leading to network partition. Therefore, to enhance the network lifetime; it is desirable to incorporate energy efficiency in routing protocols.

A node transmitting with maximum power, not only expend more energy but also increases the interference. The likelihood of a network partition is more when nodes transmit with minimum power. Therefore, the transmission power of nodes needs to be adjusted adaptively to reduce power consumption and minimize interference in the network.

The requirements to achieve lower end-to-end delay with minimal energy consumption is a conflicting issue in wireless ad hoc networks [22, 23]. However, in some situation such as in emergency response system both of the above parameters are equally important. Lower end-to-end delay facilitates quicker decision making and the minimal energy consumption enhances the network lifetime.

In this thesis, an attempt has been made to reduce the energy consumption so as to improve the network lifetime.

1.5 Objectives of the Work

In order to enhance the network lifetime, energy conservation techniques must be applied at all layers of the protocol stack. In this thesis, a few techniques for energy conservation in the network and MAC layer are proposed. An energy aware routing scheme to enhance the network lifetime is proposed. Transmitting with maximum power, consumes more energy. A technique to minimize transmission power at a node is proposed. Further, nodes are put to sleep state in order to improve energy efficiency. A framework for post-disaster communication, intended to increase the network throughput, reduce the end-to-end delay, and enhance the network lifetime of an ad hoc network deployed for disaster response is proposed. Accordingly, we identify the objectives of the thesis, and list them as follows:

- To design a routing protocol in MANET, for selecting energy efficient path.

- To propose a technique to achieve load balancing and minimize congestion in the network.
- To develop a technique to minimize the transmission power at the node level.
- To propose a framework for post-disaster communication.
- To study through simulation the performance of the above techniques.

  We have simulated using QualNet 4.5 simulator [24].

1.6 Organization of the Thesis

Rest of the thesis is organized into the following chapters:

In **Chapter 2,** we briefly discuss different energy management issues and challenges in wireless ad hoc networks. A few energy efficient protocols are analyzed based on their strength and weakness.

Chapter 3 proposes an energy efficient routing technique to maximize the network lifetime. The cost metric to compute a path between source-destination pair is based on the residual battery power and energy consumption rate at nodes. It also attempts to minimize the over-utilization of nodes on a path. Variable transmission power for data packets further reduces the energy consumption in the network. We compare the performance with AODV [1] and LER [2].

In **Chapter 4**, we propose a hybrid energy efficient protocol based on topology control and power management approach. The transmission power of a node, is determined from its neighborhood information. A node goes to sleep state in order to reduce the energy consumption, when it has no traffic to participate and its absence doesn't create a partition in its neighborhood. Performance is compared with the contemporary proposals.

Chapter 5 proposes a framework for post-disaster communication using wireless ad hoc network. The proposed framework includes: (*i*) a multi-channel MAC scheme to achieve higher network throughput, (*ii*) a node-disjoint multipath routing to minimize end-to-end delay, and (*iii*) a power control technique to reduce the interference. The performance of the proposed framework is compared with an existing framework [25].

In **Chapter 6**, we summarize the work done, highlight the contribution and suggest the directions for possible future work.

Chapter 2

Energy Aware Protocols in MANETs

2.1 Introduction

Energy efficiency has become a pervasive issue in all layers of communication protocols, as well as on a wide range of technological applications spanning from micro-electronic systems to wireless sensor networks. Until recent past, research and development in the field of communication networks was mainly targeted at their functionality and performance. Now energy efficiency has drawn a significant attention among the researchers due to the introduction of battery operated devices. Energy efficiency is one of the most crucial design criteria for mobile ad hoc networks (MANETs), as nodes are battery operated. If a node runs out of battery, its ability to route traffic gets affected. This adversely affects the network lifetime as well as degrades the performance. Network lifetime can be enhanced by minimizing the power consumption and/or maximizing the battery power of a node. Though a considerable progress has been made in the battery technology front in recent years, yet, it is incomparable with the progress made in semiconductor technology. Battery life has not kept pace with advances in mobile devices. To enhance the lifetime of mobile devices, it necessitates the requirement of power conservation techniques to enhance the network lifetime. Such techniques can be applied at different layers of protocol stack. In recent years, various techniques have been proposed to achieve energy efficiency at protocol level. These techniques adopt different approach to achieve energy efficiency. A few of them are: energy-efficient path selection, adjusting transmission power dynamically, reducing maximum transmission power at node level, adaptive sleeping, use of directional antenna, etc.

In this chapter, we discuss the need of energy management, various issues and challenges in energy management, and the techniques proposed in the literature for energy saving in ad hoc networks.

2.1.1 Need of energy management

Now a days devices are getting more and more mobile. These mobile devices are usually powered by a battery source. In some applications, replacement or re-charging of battery is infeasible. If the battery gets exhausted, device becomes dysfunctional. As the battery capacity is limited, to enhance the device lifetime some energy management technique needs to be applied. The primary reasons behind the energy management in ad hoc networks are as follows:

Limited battery capacity: Nodes in wireless ad hoc networks are battery operated, which must be judiciously used to increase the network lifetime. In many applications like disaster management, battle field communication, environmental monitoring, etc., networks should remain active as long as possible. To increase the network lifetime, attempt should be made to minimize the power consumption at nodes.

Relay traffic: Nodes in ad hoc network act as a source as well as a router to relay traffic from other nodes in the network. These relay nodes play a vital role in determining the network lifetime. If the proportions of relay nodes are large in a network, then it may lead to faster depletion of node's battery power. For lesser number of relay nodes in the network, nodes have to transmit with maximum power. Transmitting with maximum power not only depletes a node's energy but also increases the interference.

Interference reduction: Interference not only degrades the network throughput and node's lifetime but also the main cause of bad carrier sensing. Selection of optimal transmission power can reduce the interference to a greater extent.

2.1.2 Causes of energy waste

Energy waste takes place, when a node expend energy, but no useful work is done. Followings are the basic causes of energy waste in a wireless ad hoc network:

Carrier sensing: MAC protocols for wired networks such as CSMA/CD, ALOHA are not suitable for wireless networks due to the physical characteristics of wireless medium. Carrier sensing is a challenging task in wireless network. A node expend maximum energy in carrier sensing, which is also affected by hidden and exposed terminals.

Collision: Retransmission occurs due to collision, and this increases per packet energy consumption. Retransmission also affects other network parameters such as: *end-to-end delay, jitter, throughput* etc.

Idle channel sensing: Continuous monitoring of an idle channel for possible traffic consumes energy without doing any useful work. Experimental results [26] have shown that idle power consumption is nearly equal to receive power consumptions. Therefore, it can not be ignored from power consumption point of view. Reducing idle power consumptions is a major task of all energy efficient protocols in ad hoc network.

Overhearing: When a node transmits a packet, it is overheard by the neighbors within its transmission range. Thus, a node expend its energy by receiving a packet even though it is not destined to the node.

Higher bit rate and larger packet size: Higher bit rate and larger packet size, consumes more power as compared to lower bit rate and smaller packet size. Larger packet size also increases the probability of re-transmission due to collision.

Message flooding: Message flooding has following disadvantages [27, 28]: *(i) redundant transmission*: due to overlapping region, a node may receive many redundant message from its neighbors, *(ii) medium contention*: when a broadcast message is transmitted by a set of nodes in an overlapping region, there may be severe contention for the medium in that region, and *(iii) resource blindness*: flooding mechanism does not consider the available battery power at the time of transmission.

Dynamic topology: Due to node mobility, frequent path break may take place. This necessitates route discovery and route maintenance, which consumes energy.

2.1.3 Energy consumption behavior

We discuss below the energy consumption behavior of MANETs at two levels: (*i*) network interface level, and (*ii*) network traffic level.

(i) Network interface level

Energy consumed at the network interface depends on its operating states. Network interface can be in one of the following states: *transmit, receive, idle*, and *sleep*. Energy consumption in transmit state is higher than receiving state. A node in idle state neither transmit nor receive but continuously monitor the channel for a possible traffic. Therefore, the energy consumption in idle state is nearly equal to that of receiving state. Sleep state consume least amount of power among all the states. Table 2.1 shows power consumption measurements for IEEE 802.11 (2.4 GHz) interface [26]. It is observed from the Table 2.1 that, for the purpose of power conservation the network interface must be put into sleep state for longer period of time.

Table 2.1: Energy consumptions

Interface	Transmit (watt)	Receive (watt)	Idle (watt)	Sleep (watt)	Mbps
Aironet PC4800	1.4-1.9	1.3-1.4	1.34	0.075	11
Lucent Bronze	1.3	0.97	0.84	0.066	2
Lucent Silver	1.3	0.90	0.74	0.048	11
Cabletron Roamabout	1.4	1.0	0.83	0.13	2

(ii) Network traffic level

Some energy consumption measurement at different traffic level is presented in [29]. The amount of network energy consumed for each packet is the sum of cost incurred by the source and all receivers. Energy expend by a node in a point-to-point traffic is different from broadcast traffic. Potential receivers are the destination node, and nodes in the radio range of the source. Energy consumption includes: (i) *Fixed cost*: associated with channel acquisition, and (ii) *Incremental cost*: associated with packet size. The cost associated with transmitting a packet is given in Equation 2.1.

$$Cost = m \times size + b \tag{2.1}$$

where b is the fixed cost and m is the incremental payload cost.

In broadcast traffic there is one sender and many receivers. Sender access the channel before sending the data. Energy cost associated with broadcast traffic is given in Equation 2.2.

$$Cost_{broadcasting} = (m_{send} \times size + b_{send}) + \sum_{n\epsilon(\omega)S} (m_{recv} \times size + b_{recv}) \quad (2.2)$$

where b_{send} and b_{recv} are channel acquisition costs for sending and receiving the packets respectively, and m_{send} and m_{recv}, are the payload cost for sending and receiving packets respectively, and $\omega(S)$ is a set comprising all the nodes within the transmission range of the source node S.

In point-to-point traffic, there exists one source and one receiver. The energy cost for point-to-point traffic at sender and receiver is given by Equations 2.3 and 2.4 respectively.

$$Cost_{point-sender} = b_{send-rts} + b_{recv-cts} + m_{send} \times size + b_{send} + b_{recv-ack} \quad (2.3)$$

$$Cost_{point-receiver} = b_{send-cts} + b_{recv-rts} + m_{recv} \times size + b_{recv} + b_{send-ack} \quad (2.4)$$

where $b_{send-rts}$, $b_{send-cts}$ $b_{send-ack}$ are the sending cost associated with RTS, CTS and ACK packets respectively, while the corresponding receiving costs are $b_{recv-rts}$, $b_{recv-cts}$ $b_{recv-ack}$.

2.1.4 Energy model

The amount of energy consumed to transmit one data packet is given as:

$$E_{data} = E_{src} + E_{dest} + \sum_{n=1}^{HC} E_{relay} \quad (2.5)$$

where, E_{src}: Energy consumed at the source node,
E_{dest}: Energy consumed at the destination node,
E_{relay}: Energy consumed by relay nodes, and
HC: Hop count.
E_{src} is given by Equation 2.6,

$$E_{src} = \begin{cases} E_{Tx_{(RREQ)}} + E_{Rx_{(RREP)}} + E_{Tx_{(DATA)}} & ; if \text{ path does not exist} \\ E_{Tx_{(DATA)}} & ; if \text{ path exists} \end{cases} \quad (2.6)$$

E_{dest} is given by Equation 2.7,

$$E_{dest} = \begin{cases} E_{Rx_{(RREQ)}} + E_{Tx_{(RREP)}} + E_{Rx_{(DATA)}} & ; if \text{ path does not exist at the source node} \\ E_{Rx_{(DATA)}} & ; if \text{ path exist at the source node} \end{cases} \quad (2.7)$$

E_{relay} is given by Equation 2.8,

$$E_{relay} = \begin{cases} E_{Rx(RREQ)} + E_{Tx(RREQ)} + E_{Rx(RREP)} + E_{Tx(RREP)} + E_{Tx(DATA)} + E_{Rx(DATA)} \\ \qquad ... \ ; if \text{ path does not exist at the source node} \\ E_{Rx(DATA)} + E_{Tx(DATA)} \\ \qquad ... \ ; if \text{ path exist at the source node} \end{cases} \tag{2.8}$$

where, $E_{Tx(RREQ)}$: Energy consumed in transmitting RREQ packet,
$E_{Rx(RREQ)}$: Energy consumed in receiving RREQ packet,
$E_{Tx(RREP)}$: Energy consumed in transmitting RREP,
$E_{Rx(RREP)}$: Energy consumed in receiving RREP,
$E_{Tx(DATA)}$: Energy consumed in transmitting data packet, and
$E_{Rx(DATA)}$: Energy consumed in receiving data packet.

2.2 Power Saving Protocols

Different energy-aware protocols have been proposed to improve energy efficiency in all layers of MANETs protocol stack [30–36]. Most of these proposals focused on network layer and MAC layer to conserve energy. The goal of power conservation technique at network layer is to select an energy efficient path between a source-destination pair, so as to: (*i*) achieve maximal energy saving during delivery of a single packet, and (*ii*) enhance network lifetime.

Power saving issues at MAC layer includes: (*i*) hidden and exposed terminal problems, (*ii*) interference and collision, (*iii*) directional antennas, etc. Hidden and exposed terminals are inherent to wireless ad hoc networks. The transmission from a hidden node interfere with the on-going transmission and the exposed nodes are prohibited to transmit for the period of on-going transmission. A few attempts have been made to minimize the effects of hidden and exposed terminals [37–39].

Interference causes collision and there exist no mechanism to detect collision in wireless ad hoc networks. Retransmission due to collision consume network bandwidth and waste energy. Though the request-to-send (RTS) and clear-to-send (CTS) mechanism can minimize collision, yet it cannot be eliminated. A few schemes to minimize collision are reported in [40, 41]. Use of directional antenna can reduce interference and enhance energy saving in wireless ad hoc networks [42–45].

Power-aware protocols can be broadly classified into the following types: (*i*) Active power saving protocols, (*ii*) Passive power saving protocols, and (*iii*) Topology control protocols.

In the following sub-sections, work reported in the literature corresponding to each of the above classification is highlighted.

2.2.1 Active power saving protocols

Active power saving protocols attempts to: (i) achieve maximal energy saving in delivering a single data packet, and/or (ii) enhance network lifetime; using the path more intelligently. Protocols whose main goal is to select an energy efficient path between source-destination pairs falls under this category. Several energy metrics are used to determine energy efficient path. A few of the active power saving protocols are discussed below.

Minimum total transmission power routing (MTPR) [46] selects a path based on the minimum transmit energy. Total transmission energy for a route, P_i, is calculated as: $P_i = \sum_{i=1}^{d} E(n_i, n_{i+1})$, where $n_1, n_2, ..., n_d$ are the nodes in the route between the source n_1 and destination n_d respectively. $E(n_i, n_j)$ denotes the energy consumed in transmitting over a link (n_i, n_j). The optimal path, P_{opt}, is selected based on following condition:

$$P(opt) = \min_{j \in P^*} P_j$$

where P^* is the set of all possible paths.

In the routing scheme based on battery power cost, a path is selected depending on the remaining battery power of a node. A path with maximum path cost is selected as an optimal path, where the path cost is described as minimum value of residual battery of all the nodes on the path. One such routing scheme based on battery power cost is Min-Max Battery Cost Routing (MMBCR) [47]. The path cost in MMBCR is given as:

$$P(r_j) = \max_{\forall n_i \in r_j} f_i(t)$$

where $f_i(t)$ is the battery power cost function of node i at time t, and r_j is the battery power cost of path j at time t. An optimal path is selected which satisfies the following condition:

$$P_{(opt)} = \min_{r_j \in P^*} P(r_j)$$

where P^* is the set of all possible paths. The above metric can extend the mobile node lifetime but it does not guarantee that the total transmission energy in a network is minimized. To overcome this a hybrid approach called Conditional Max-Min

Battery Capacity Routing (CMMBCR) [47] was proposed which considers the merits of both the minimum transmission power routing and Max-Min battery power routing. CMMBCR also does not guarantee that the nodes with higher residual battery capacity will survive under heavy traffic.

A path with maximum remaining lifetime of nodes is selected in lifetime based prediction [48]. Objective of lifetime prediction routing is to extend the network lifetime in a dynamic environment. Routing metric considered in lifetime based prediction is defined as:

$$\max_{p}\ L_p(t) = \min_{i \in p} P_i(t)$$

where $L_p(t)$ is the lifetime of path p at t, and $P_i(t)$ is the predicted lifetime of a node i on the path p. In this approach each node maintains the time instances of last N packets it has sent or received, and the corresponding residual energy to estimate its lifetime.

Lifetime enhancement routing (LER) [2] considers the residual battery and transmission power of a node to determine the lifetime of the node. The optimal path between a source-destination pair is computed as:

$$P(opt) = \ \min \sum_{i,j \in V} \frac{RB_i(t)}{TP_{ij}(t)}$$

where, $RB_i(t)$ is the residual battery power of node i and $TP_{ij}(t)$ is the required transmission power from node i to node j.

In energy efficient ad hoc on demand routing (EEAODR) [49], residual battery is considered as the route cost to select a path. A path P_i is calculated as: $min(RB_a, RB_b, ...RB_c, RB_d)$, where RB_x is the residual battery power of nodes on the path P_i. Nodes which does not participate in the on-going transmission are put to sleep state to conserve energy.

2.2.2 Passive power saving protocols

The basic objective of passive power saving protocols is to put the nodes in idle state to sleep state in order to save energy. A few power management protocols for ad hoc networks are discussed below:

There are two types of power management in IEEE 802.11 DCF [50]. They are: (i) power save (PS) mode for infrastructure based wireless network, and (ii) Independent Basic Service Set (IBSS) mode for ad hoc network. We discus below the power management in IBSS mode, as it is relevant to wireless ad hoc networks. In this mode, synchronized beacon intervals are established by the node which initiates the IBSS, and is maintained in a distributed fashion. It defines the fixed size length, *Announcement Traffic Indication Message* (ATIM) window. A node transmitting an ATIM frame shall remain awake for the entire duration of the current beacon interval. Nodes wake up at the beginning of the beacon interval (BI) and remain *awake* till the end of the ATIM window. A node transmits RTS-CTS control frame, beacon and ATIM management frame during the ATIM window. Nodes participating in the traffic announcement remain awake till the end of beacon interval, and the non-participating nodes go to sleep state at the end of the traffic window. Beacon announcement and acknowledgment is transmitted during the ATIM window to avoid contention with the data traffic. Figure 2.1 shows the data transmission in IBSS mode. The effectiveness of IBSS mode depends on the ATIM window and beacon interval. For a shorter ATIM window, there will not be enough traffic; whereas for a longer ATIM window, the duration for which a node remains awake is longer causing more power consumption. Similarly, if the beacon interval is too short, then the overheads associated with traffic announcements and sleep-awake cycle will be higher. For a longer beacon interval more number of nodes will announce their traffic at each ATIM window. This increases contention as the number of participating nodes increases.

Clock synchronization is a major limitation of IEEE 802.11 IBSS mode. Synchronization, is difficult to achieve due to unpredictable node mobility, and communication delay in wireless ad hoc networks. Tseng *et al.* [51] have proposed a power management based protocol called *Dominating-Awake-Interval* for multi-hop ad hoc networks. It is based on multiple beacons and overlapping awake intervals. The beacon interval consists of three windows: *active window, beacon window* and *multi-hop traffic indication message* (MTIM) window. Beacon window and MTIM window are the parts of active window as shown in Figure 2.2(a). MTIM window is similar to ATIM window of IEEE 802.11 IBSS mode. A node deciding to enter into the power save mode, divides the time axis into fixed length beacon intervals, which are alternatively labeled as odd and even. This is shown in Figure 2.2(b). In the odd beacon interval, an active window begins with a beacon window followed by MTIM window, and in even beacon interval, an active window is always terminated by a beacon window. Beacon intervals are alternatively designed as even and odd, so that both the node can able to access each other. For example, node A responds to node B in the even beacon interval and vice-versa in odd beacon interval; shown in

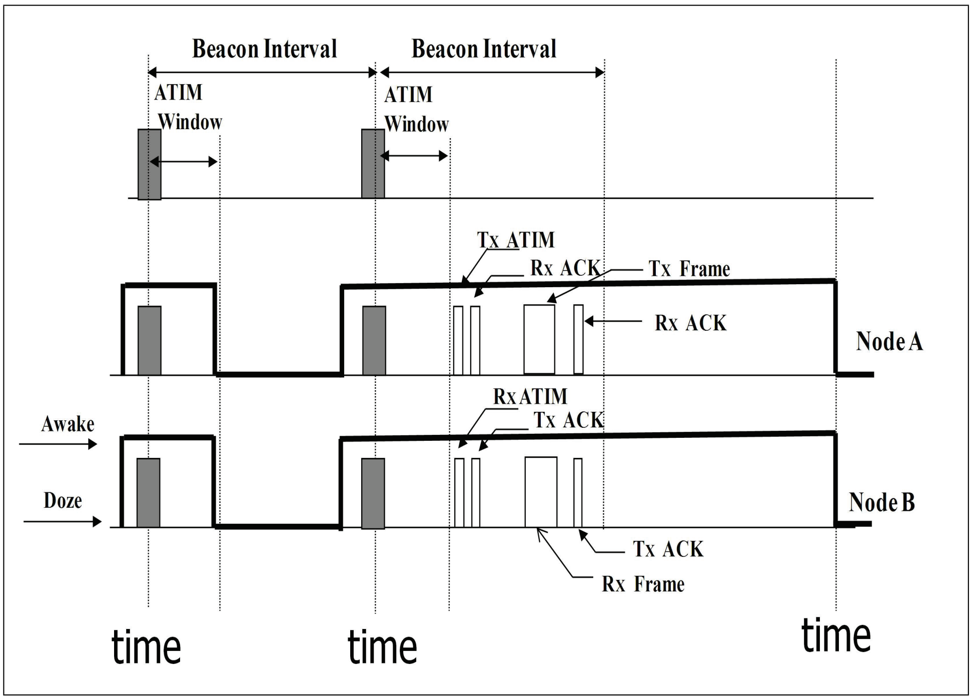


Figure 2.1: Data transmission in IBSS mode.

Figure 2.2(b). However, a node remains awake for a longer period of time compared to *IEEE 802.11 DCF*.

Another variation of IEEE 802.11 DCF power save mode is *Dynamic Power Saving Mechanism* (DPSM) [52] which dynamically selects the size of ATIM window based on network conditions to optimize power saving. Size of an ATIM window is increased when their exists packets for transmission after expiry of the current ATIM window. Nodes on overhearing the marked packet modify their length of ATIM window. A marked packet indicates failure to deliver the corresponding ATIM frame in the last few attempts. If a sender could not complete all its pending traffic in the current beacon interval, then both the sender and receiver node will stay up for the next beacon interval. After delivery of all pending packets, both the sender goes to sleep mode immediately. A node can dynamically adjust its ATIM window based on: (*i*) pending packets, which are not announced during the current ATIM window, (*ii*) over-hearing of larger ATIM window size, (*iii*) receiving an ATIM frame after expiry of the ATIM window, and (*iv*) On receiving a marked packet. Nodes based on the above condition adjust its ATIM window size at the beginning of next beacon interval. Though power saving in DPSM is better compared to IEEE 802.11 DCF, yet, it is more complex in selecting ATIM window size.

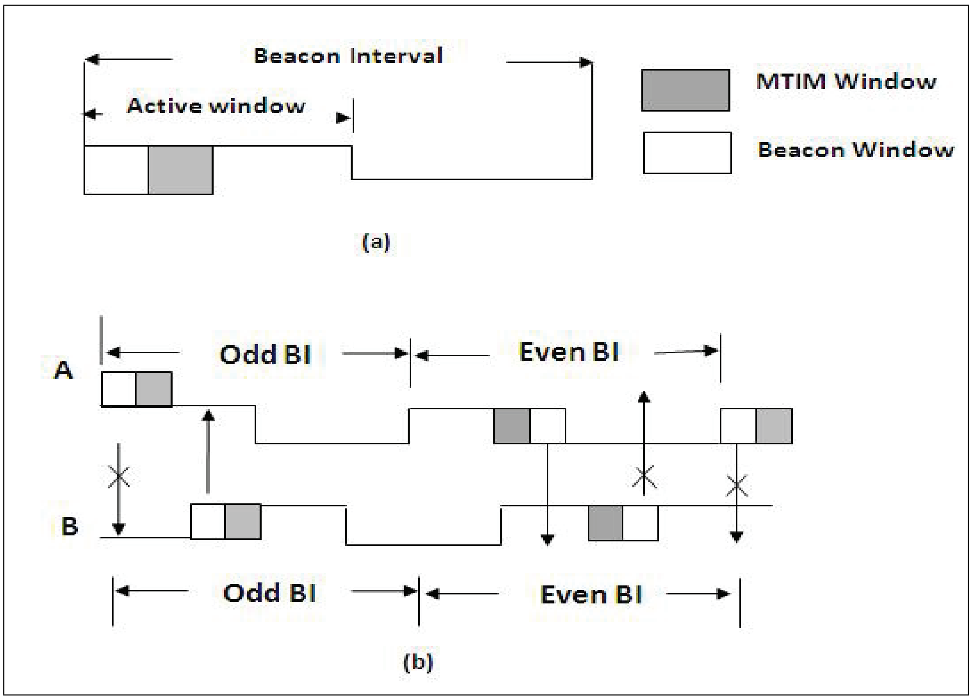


Figure 2.2: Beacon interval: (a) Active window, beacon, and MTIM window; (b) Even and odd beacon interval.

Power Aware Multi-Access with Signaling (PAMAS) protocol [53], uses different channels for data and control. RTS/CTS packets are transmitted over control channel while data are transmitted over data channel. Signaling channel enable nodes to determine when and how long they can power off themselves. Receiving node transmit a busy tone over the control channel to inform others, that the data channel is busy.

Power saving in PAMAS varies from 10% - 70% depending on the network type. Network with higher node density and traffic load saves more energy, but it is affected in sparsely connected network under light load condition.

Two power management based protocols: (*i*) Basic Energy-Conserving Algorithm (BECA), and (*ii*) Adaptive Fidelity Energy Conserving Algorithm (AFECA) is proposed in [54]. BECA and AFECA turns off the node's radio as often as possible to save power. They use information from application layer, and based on the traffic condition decides when to switch ON and OFF the radios. Nodes can be in one of three following states in BECA: *sleeping*, *listening*, or *active*. A timer associated with each state determine how long a node will remain in that state. Initially, nodes are in the listening state. They enter to sleep state, if no traffic is received within the specified listening time. A node goes to active state, when it has some pending traffic. As nodes take their own decision about the state transition maintaining a path to destination is a major issue in BECA. AFECA uses variable sleep time and takes advantage of node density. Nodes in dense areas goes to sleep after a longer period of time. Sleep time depends on the number of neighbors a node have. At any given time only one nearby node wakes up to hear the RREQ packet while other nodes will be in sleep state. AFECA performs well in a network having uniform node density. Energy-saving in AFECA is no more superior to BECA, but it enhances the network lifetime. Energy saving at AFECA and BECA comes at the cost of higher packet loss and longer route setup latency.

In a light traffic condition, a node having lesser traffic to forward also remain in active state for the entire beacon period and this unnecessarily consume energy. To deal with the above traffic pattern, a traffic aware power saving protocol is proposed in [55]. It allows a node to enter into sleep state when it has no more data to deliver. However, this scheme requires clock synchronization.

2.2.3 Topology control protocols

Topology control approach conserves energy by adaptively adjusting the nodes transmission power while maintaining the network connectivity. Most of the topology control protocols require information such as location, direction, neighborhood, etc, to construct the topology. Location information can be obtained through global positioning systems (GPS) or other positioning methods. The directional information can be obtained using angle-of-arrival (AOA) technique, and the neighborhood information can be obtained by exchanging information among the nodes. A few topology control protocols are discussed below:

Location Based Approach: This approach produces accurate topology but are associated with higher hardware cost. In order to reduce the hardware cost some of the location based techniques assume that a subset of nodes are equipped with GPS while other nodes can obtain their location information by exchanging message with GPS enabled nodes. A few representatives of this approach are:

Local Minimum Spanning Tree (LMST) protocol [56]: It operates in three phases: (i) Information exchange phase: In this phase nodes send a *Hello* message containing their identity and location information, (ii) Topology construction phase: A node construct its local minimum spanning tree (MST). Link cost used in building the local MST is the Euclidean distance to its neighbor. Spanning tree constructed using link cost may not be unique. To obtain a local MST the protocol defines a link weight function, and (*iii*) Determination of transmission power: Transmission power to a neighbor is derived from the received signal strength of *Hello* message. Power required to send a message to any neighbor is obtained from the constructed topology. A node also determine its broadcast power which is the minimum power needed to reach the farthest node in its neighborhood.

R & M protocol [57] is based on relay region and enclosure graph. In this approach, communication through relay node is preferred and the communication is all-to-one. It attempts to find the most energy efficient node in the relay region for communication. R & M operates in two phases. In the first phase, nodes broadcast a beacon message containing their identity and location information. After receiving beacon information from neighbors, a node compute the enclosure graph based on the relay region. A relay region (RR) of a certain transmitter-relay node pair (u, w) is defined as:

$$RR(u \to w) = \{(x, y \in \ R^2 \ : \ P_{u\to w\to(x,y)} \ < \ P_{u\to(x,y)})\}$$

where nodes u, w identify the set of points in the plane (x,y)through which communication $P_{u\to w\to(x,y)}$ is energy efficient when compared to direct communication $P_{u\to(x,y)}$. Sometimes, relay region is used to define the enclosure of a node. Enclosure of node u, which represents the area of the plane beyond which it is not energy efficient for node u to search for one-hop neighbors. The shape of the relay region depends on the radio propagation model, and the value of distance power gradient. A node in the relay region is marked as dead or alive. Node is said to be dead, if it belongs to the relay region of another node. Otherwise, the node is marked as alive. After receiving neighboring information, a node determines its neighbor set, which includes only the alive members. Then, the protocol uses a function called *Flip-All-States-Down-Chain* to update the dead and alive nodes state. In the second phase, minimum energy needed to reach the master node is computed using enclosures graph. Each node computes the minimum energy required to reach the master node. Data transmission takes place after the establishment of minimum energy path. Though, R&M protocol conserve energy and preserve network connectivity, yet it increases message overhead.

Direction Based Approach: In this approach, it is assumed that nodes can determine the direction of signal received from other nodes. There are many techniques to get direction information. Details of it can be obtained from IEEE Antenna and Propagation community [58]. A few of the direction based approach is explained below.

Cone Based Topology control (CBTC) protocol [59] uses directional information to construct the topology. It operates in two phases. In the first phase, a node determines the minimum power required to reach its neighbors in all directions. Then, it exchange information with other nodes to identify energy efficient edges, and remove the inefficient links from the topology. CBTC uses two types of messages *viz.* beacon and acknowledgment (ACK). Beacon message contains sender identity and is transmitted with a power $p \leq P_{max}$, where P_{max} is the maximum power of the node. Nodes on receiving a beacon message send an ACK. Though, CBTC saves a good amount of energy and maintain network connectivity, yet its message complexity is higher due to beacon-ACK message handshaking.

Borbash and Jennings [60], performed an extensive simulation on different topology and found that relative neighborhood graph (RNG) gives better results. Distributed relative neighborhood graph (DRNG) is based on RNG. It can compute the RNG in distributed as well as localized manner. A node computes the RNG with lesser transmission power with lesser $p(u) \leq P_{max}$. This continue until the covered region is equal to 2Π or the current transmission power $p(u)$ reaches maximum limit P_{max}. The neighborhood covered region is shown in Figure 2.3. The neighbor coverage of node **X** is defined as the cone of width $\overbrace{BYD}$ centered at **Y** *i.e* the shaded area of $BYDX$. The covered region of node **Y** is the union of the covered region of node **X** and **Z**.

The difference between DRNG and CBTC is that, the former includes uncovered nodes in the set of selected neighbors and its message complexity is lesser than CBTC. Other features of DRNG is that it is fully distributed and has a maximal logical node degree equal to *Six*.

Neighbor Based approach: Location based approach and direction based approach have some limitation. They may not work well in certain environment and their support technology are expensive. For example, GPS may not function properly in indoor. To overcome this problem, neighbor based approach is proposed. In this approach a node determines its neighbor set adaptively and then computes its transmission power based on the neighbor set. Every node in the network is connected to the k-closest neighbor. A few representative of neighbor based approach is discussed below:

In *k-Neighbor* protocol [61], nodes broadcast their identity at maximum power. A node on receiving the broadcast message estimate its distance to that node. Then, it computes the k-closest neighbor according to the estimated distance. A node u periodically broadcast $N(u)$ and $KN(u)$ with maximum power, where $N(u)$ and

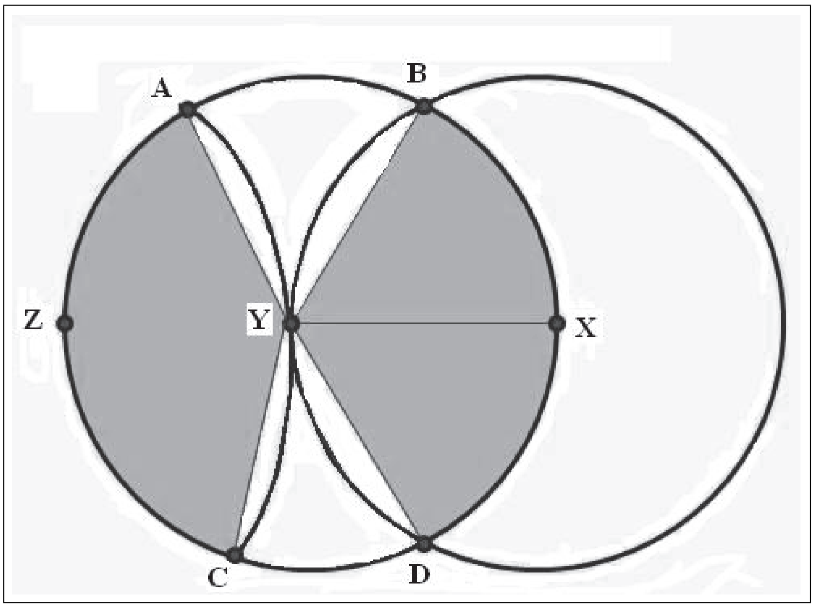


Figure 2.3: The coverage area of node **Y** is the union of coverage area of node **Z** and **X** (shown in shade).

$KN(u)$ are its neighbor set and k-closest neighbor set respectively. Exchanging their neighbor set, each node maintain their symmetric neighbors and remove their asymmetric neighbors. Transmission power $p(u)$ is obtained from $KN(u)$, which is the minimum power required to reach the farthest node in $KN(u)$.

Location Free Topology Control (LFTC) protocol [3], operates in two phases. In the first phase, each node broadcast $Hello$ message with maximum power, P_{max}, containing the sender identity and a specific data structure. Nodes in LFTC maintain a table which is updated every time a node receives $Hello$ message. Transmission power is determined from the information available in the table. In the second phase, data transmission takes place. Each node in LFTC separately determines the transmission power for data packet, and control packet. Message complexity in LFTC is higher.

In *Adaptive Neighbor-based Topology Control* (ANTC) [4] transmission range is adaptively determined in order to maintain network connectivity. Based on the local connectivity, each node selects a backbone that guarantees a hierarchical topology structure. Both LFTC and ANTC does not put the node into sleep state to save energy.

In [62], power saving tree is constructed without taking the nodes local information into account. Transmission power is controlled to maintain network topology.

Protocols like *Geographical Adaptive Fidelity* (GAF) [63] and SPAN [64], maintain a connected dominating set to conserve energy. GAF identifies the routing prospective nodes and redundant nodes. Redundant nodes are switched OFF to save energy. A few nodes are selected as coordinators in SPAN, which stay/awake continuously and perform multi-hop packet routing. Nodes other than the coordinators remain in power save mode to conserve energy.

2.3 Network Simulators for MANETs

In this section we have described the most widely used network simulators in the research field. Simulators that are mostly used for MANET simulations are: OPNET, QualNet, OMNeT++ and NS-2. We briefly summarize these simulators here.

OPNET [65]: It is a commercial network simulator used for simulations of both wired and wireless networks. It supports a wide range of wireless technologies such as IEEE 802.11 wireless LANs, Bluetooth, satellite networks, and WiMAX, etc. OPNET also provides a graphical editor interface to build models for various network entities from physical layer modulator to application processes, and includes graphical packages and libraries for presenting simulation scenarios and results.

QualNet [24]: It is a of the discrete event simulator. Extremely scalable and can supports high fidelity models of networks of thousands of nodes. QualNet is modeling software that predicts performance of networking protocols and networks through simulation and emulation. The simulator is written in C++ while it's graphical toolkits are implemented in Java. QualNet consists of several modules which handle specific functions like: Scenario esigner enables a user to define geographical distribution, physical connections and functional parameters of the mobile nodes. Animator module is used to execute and animate experiments created in the scenario designer. Packet tracer is a packet-level visualization tool for viewing the contents of packets. Analyzer displays network statistics generated from the qualnet experiments. QualNet is the commercial version of open source simulator GlomoSim.

NS-2 [66]: It is the open source network simulator written in C++ and requires OTcl scripts. Though NS-2 has rich suite of algorithms models, it has limitation in graphical support. The pseudo random number generator (PRNG) has to be set for each run of the simulation, else it produces identical result in each run. One of the major limitation is its scalability. It does not scale beyond few hundred nodes [67].

OMNeT++ [68]: It is an open source simulator. It offers a C++ simulation class library and GUI support. The simulator can be used for many applications such as: traffic modeling of telecommunication networks protocol, ad hoc and sensor network applications, etc. OMNeT++ comes with far less pre-built modules and protocols than the other network simulators. It is basically a framework, which can include different networking modules with less complexity.

We preferred QualNet over other due to its powerful features and scalability. The details of it is mentioned in [69].

2.4 Summary

In this chapter we discussed the various issues and challenges, and the need for energy management in mobile ad hoc networks. Energy management in MANETs can be broadly categorized into the three approach: Active power saving, Passive power saving, and Topology control.

The objective of active power saving protocols is to find an energy efficient path to maximize the network lifetime. In passive power saving techniques nodes are put to sleep state to conserve energy. The amount of energy saved is proportional to the time nodes spent on sleep mode. However, this saving comes at the cost of higher end-to-end delay. In topology control approach node adaptively adjusts its transmission power in order to conserve energy. This also helps to minimize the interference level in the network.

Various power conservation techniques, belonging to each of the above three approaches are discussed in this chapter. Energy saving can be done at all layers of the MANET protocol stack. But majority of the energy saving protocol is focused at the MAC layer and network layer.

In the rest of this thesis, we present the work done to enhance the lifetime of MANET.

Chapter 3

An Energy Efficient Routing Protocol for MANET

3.1 Introduction

Routing is the basic mechanism of determining the route between a source-destination pair. Due to unpredictable node mobility the topology of wireless ad hoc networks changes dynamically. As a result the routing protocols developed for wired networks are not suitable for wireless ad hoc networks. Thus, efforts are being made by the researchers on studying, defining and evaluating the new routing protocols for decentralize wireless ad hoc networks. Most of the routing protocols developed for MANETs are based on hop-count metrics, which does not takes into account the battery power of a node in path selection. Therefore, they are not suitable for applications such as emergency response system, battlefield communication, etc. In these applications battery power is a key issue, as the network operational time depends on battery. Thus, efforts are being made on developing energy aware routing protocol for selecting a path. These protocols attempts either to minimize the energy consumed in forwarding a data packet between the source-destination pair or maximize the network lifetime using the path and resources more intelligently.

Most of the energy based protocols select the residual battery capacity of nodes as the routing cost metric [49, 74–76]. However, this doesn't guarantee for any increase in the network lifetime [21, 77–79]. For example, some nodes on the path that forward large volumes of data may die due to over utilization of that path.

In this chapter, we proposed: (*i*) a new cost function to compute the lifetime of nodes, (*ii*) cost metric for selecting a path, and (*iii*) a mechanism to minimize the over utilization of a node on the path. The proposed routing scheme uses an energy aware cost metric in selecting a path. It also employs a mechanism to minimize the over utilization of a node on the path. Variable transmission power is used for data traffic.

3.2 Protocol Description

In this Section we describe the proposed scheme. The proposed route cost metric and path selection is described Section 3.2.1. Technique to minimize the over-utilization of a node is explained in Section 3.2.2. Computation of variable transmission power is explained in Section 3.2.3. Working of the proposed scheme with an example is explained in Section 3.2.4.

3.2.1 Route cost metric

The proposed cost function to compute the lifetime of a node is based on the following: *(i)* Residual battery (RB) power, and *(ii)* Energy consumption rate (CR) at the node. A node monitors the amount of energy consumed per transmission, reception and overhearing, and computes the energy consumption rate in every T sampling seconds. A value of T is determined as given in [75]. Let the energy consumption rate of a node u at time t is $CR_u(t)$ and its residual battery be $RB_u(t)$. Let $LT_u(t)$ be the lifetime of node u, at time t.

$$LT_u(t) = \frac{RB_u(t)}{CR_u(t)} \tag{3.1}$$

The energy consumption rate $CR_u(t)$ is given by Equation 3.2 [75].

$$\mathrm{CR_u}(t) = (1 - \eta) \times CR_{old} + \eta \times CR_{new} \tag{3.2}$$

where CR_{old} and CR_{new} represents the last and newly calculated value of energy consumption rate respectively and $\eta(< 1)$ is a weight function. We assigned higher priority to CR_{new} by setting η to a larger value.

Consider a path $P_i = (u_1, u_2, ..., u_d)$ where u_1 is the source and u_d is the destination. Let PL_i be the lifetime of path P_i. We compute PL_i as given in Equation 3.3.

$$PL_i = \min_{\forall u \in V} \{LT_u\} \tag{3.3}$$

where V is the set of nodes between the source-destination pair. Route request (RREQ) packet carries the information about the intermediate nodes between a source-destination pair. Destination node on receiving the first RREQ packets from a source starts a timer after the expiry of the timer it computes the lifetime of all the paths for which it has received the RREQ packet between the source-destination pair, and selects an optimal path as given in Equation 3.4.

$$P_{(opt)} = \min_{\forall j \in P^*} \left\{ {}^{1}\!/_{PL_j} \right\} \tag{3.4}$$

where P^* is the set of paths between a source-destination pair.

3.2.2 Minimizing node overutilization

An overutilized node can diminish the network lifetime. When a heavy traffic is routed over a path, the critical node on the path may exhaust its battery and die. This affects the network connectivity and reduces the network lifetime. An attempt has been made to minimize the overutilization of nodes between a given source-destination pair. In the proposed scheme each node limits the number of connection requests that can be established through it to a particular destination. A node drops the RREQ packet, if the number of connection requests between a source-destination pair exceeds the limit. After dropping the RREQ packet it then reset the connection limit for that destination to *One*. This is done because a node that dropped the route request packet may be the critical node for the establishment of a path between the requested source-destination pair. The connection limit is reset to *One*, so that the node will forward the subsequent RREQ packet and a path to the destination can be established. For example, on receiving a route reply (RREP) packet from a destination **X** a node say **Z** decrements the number of connections that can be established to **X** through it by *One*. The node **Z** drops the RREQ packet to **X** when the number of connections that can be established to **X** through it has reached to *Zero*. After dropping the RREQ packet it resets the connection limit to node **X** to *One*. This is because node **Z** may be a critical node for establishment of path between a node say **M** and **X**. A node rebroadcast the RREQ packet only when a path to the destination could not be established. The connection limit can minimize the overutilization of a node. Further, load balancing can be achieved and the flooding of RREQ packets in the network can also be reduced [80–82].

3.2.3 Computation of transmission power

In the traditional on-demand routing protocols for MANET, both the data and control packets are transmitted with maximum power. When a packet is transmitted with maximum power it causes more interference with other transmissions. This leads to collision and increases contention for medium. Hence, it is necessary to transmit the packets at a lower power. In the proposed scheme, we apply a power control technique to transmit data packets. For data packets a node determines the transmission power that is enough to reach the next-hop node on the path to the destination. A node calculates its transmission power for data packets based on the next-hop node's geographical position and mobility pattern. A node u compute the transmission power required to reach the next-hop node v on a path as given in Equation 3.5.

$$T_x = (D + \Delta)^{\beta} + C \tag{3.5}$$

where, D is the Euclidean distance between u and v, Δ is the expected variance of distance between u and v considering the mobility, β is the path loss exponent with $2 \leq \beta \leq 4$, and C is a constant. Expected variance of distance, Δ, is calculated as given in Equation 3.6.

$$\Delta = (Current_{time} - Reply_{time}) * S_N \tag{3.6}$$

where, $Current_{time}$ is the time at which node u is computing its transmission power, $Reply_{time}$ is the time at which node u has received the RREP packet from node v, and S_N is the speed of node v.

3.2.4 Illustration

In this sub-section we illustrate the working of our proposed scheme through an example. Source broadcast a RREQ packet, to initiate the route discovery process. RREQ packet carries information such as: *source-id, destination-id, sequence number, lifetime* etc. We consider Figure 3.1 to illustrate the route discovery process. Let node **S** be the source and **D** be the destination. Source **S** broadcast a RREQ packet. In Figure 3.1, we have shown only three fields of RREQ packets: *source-id, destination-id* and *lifetime*. An intermediate node on receiving the RREQ packet, first compute its lifetime. Then the node update the lifetime field in RREQ packet if the computed value is less than the value in the received RREQ packet. Let us assume that the computed lifetime (LT) value of nodes **S, A, B, C, E** and **F** be

20, 7, 11, 6, 10 and 12 time unit respectively as shown in Figure 3.1. Lifetime of node **A** is 7 which is lesser than the value 20 in the lifetime field of RREQ packet received from **S**. Therefore, node **A** updates the lifetime field with its own lifetime and rebroadcast the RREQ packet.

No changes is made, in the lifetime field, if the computed value at a node is equal to or greater than the value in the RREQ packet. For example, the lifetime of node **F** is 12 which is greater than the value in the lifetime field of RREQ packet it has received from node **B**. Therefore, no changes is made in the lifetime field of RREQ packet at node **F**. This is shown in the Figure 3.1.

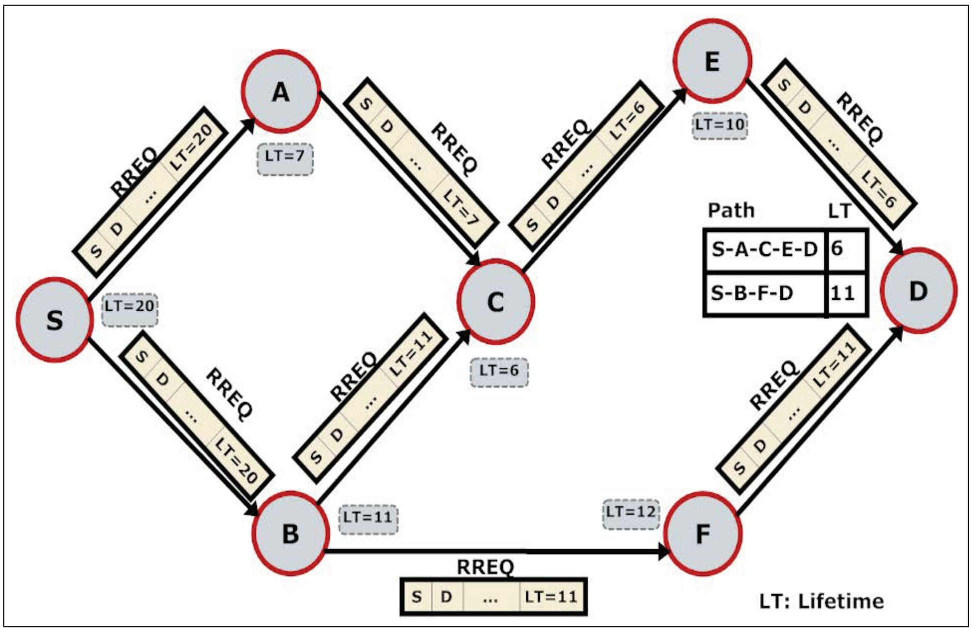


Figure 3.1: Transmission of RREQ packet.

The above process continues until the RREQ packet reaches at the destination node. A destination node on receiving the first RREQ message, starts a timer. After the expiry of the timer it computes the lifetime of all paths and selects an optimal path as discussed in Section 3.2.1. In the present example destination node **D** has received two RREQ in two paths: **S-A-C-E-D** and **S-B-F-D**. Lifetime of path **S-A-C-E-D** is computed to be 6, whereas lifetime of **S-B-F-D** is 11. The path **S-B-F-D** is choosen as the optimal path as its lifetime is higher than the path **S-A-C-E-D**.

Destination **D** selects the path **S-B-F-D** and send a RREP message. Besides other information the RREP message contains the location information of the forwarding node. A node on receiving the RREP message updates the relevant information in its routing table. The updated routing table at node **F** and **B** for the above example is shown in Figure 3.2. *Next-hop* field in the routing table indicates the next-hop node on the path to destination. *LOC* field indicates the location information of the next-hop node at the time the node has received RREP packet. *Reply-Time* indicates the time at which the node has received the RREP packet.

Each node on the path to the source, updates the *LOC* field of RREP with its own location information, before forwarding the RREP to the next hop node on the path to the source. This process continues until RREP packet reaches the source node.

Source node **S** after updating the routing table, compute the transmisssion power required to send the data packet to the next-hop node **B** based on the location information. Then, node **S** transmits the data packet to node **B** with the computed power. Each intermediate nodes on the path to destination also compute their transmission power required for the next-hop node on the path to the destination. We have assumed that nodes are moving with equal speed for computing the transmission power.

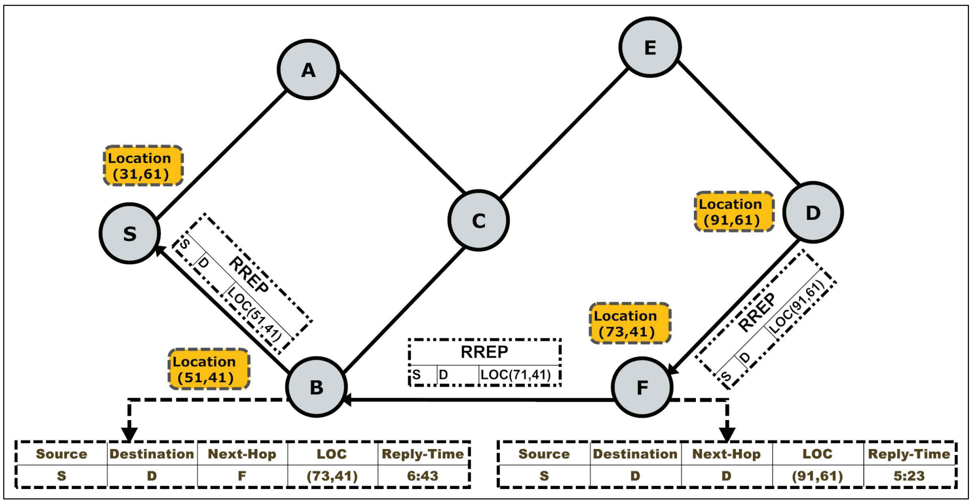


Figure 3.2: Forwarding of RREP packet and updation of routing table.

We consider Figure 3.3 to explain the minimization of overutilization of a node. Let the number of connections that can be established to destination **D** through node **B** be *Zero* at some point of time. Suppose a node **P** wants to communicate with **D**. On receiving the RREQ packet from **P**, node **B** drops the RREQ packet as shown in the Figure 3.3. Then, it sets the limit on connection that can be established to node **D** to *One*. This is shown in Figure 3.4. If a connection between **P** and **D** is established then node **B** will not be on that path. Hence, it will not be overutilized. If the connection between **P** and **D** could not be established then **B** might be the critical node for path establishment between **P** and **D**. In this case node **P** rebroadcast the RREQ packet. Node **B** on receiving the RREQ packet, make necessary modification and rebroadcast it. This is shown in Figure 3.4.

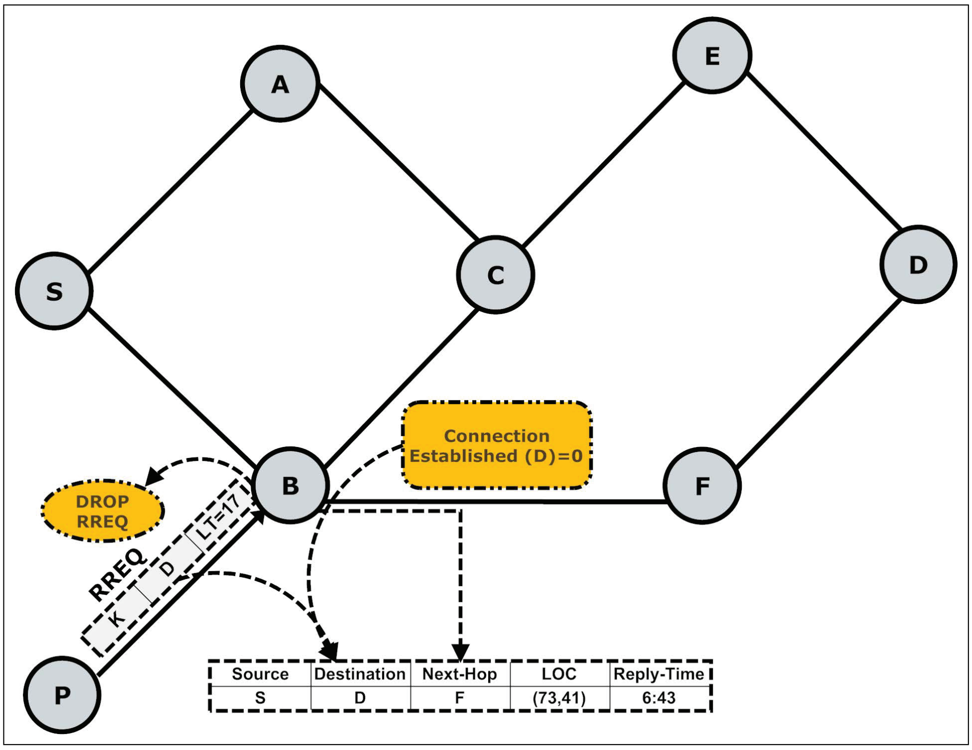


Figure 3.3: Node **B** drops the RREQ packet received from **P**.

3.3 Simulation Results

In this section we first evaluate the performance of the proposed scheme and then compare it with a few existing ones. In order to evaluate the performance of our proposed scheme, we carried out an extensive simulation using the *QualNet 4.5* simulator [69]. The initial value of $CR_{(old)}$ is taken as 0.0001 and the value of η is taken as 0.7 in this simulation. Parameters considered for the simulation are mentioned in Table 3.1.

First, we evaluate the proposed scheme, varying number of CBR connection and the number of nodes in the network. The following metrics are considered for

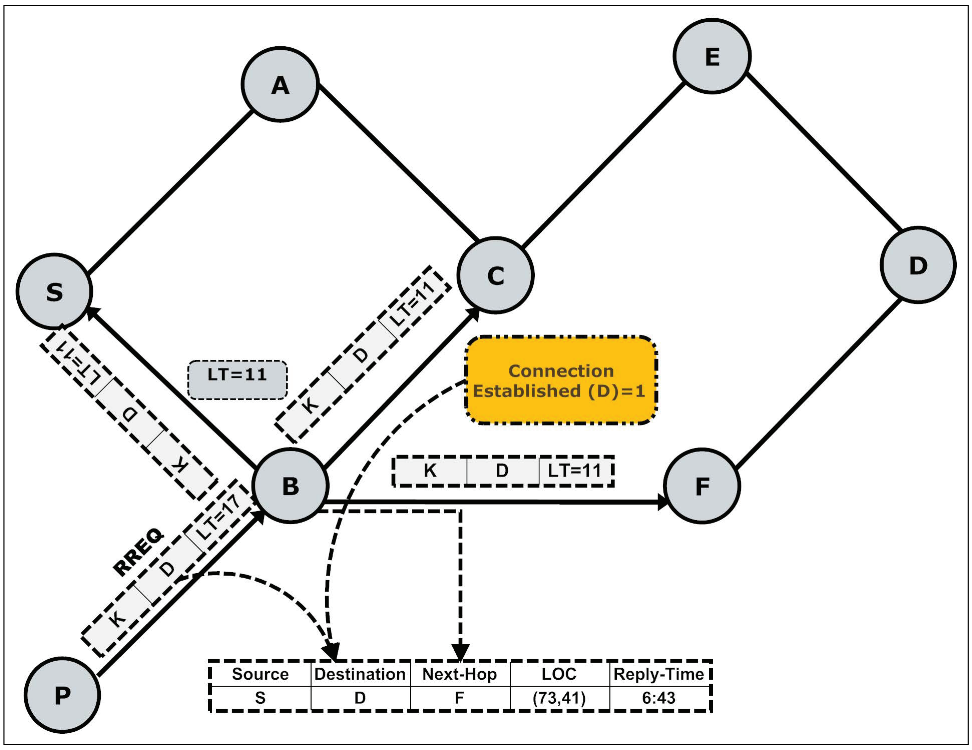


Figure 3.4: Node **B** forwards the RREQ packet from **P**.

evaluation: *energy consumption*, *network lifetime,* and *packet delivery ratio*. The number of connection that can be established through a node to a destination is varied from 1, 2, 3 and no limit (no limit indicates as there is no upper bound on the number of connection that can be established to any node).

When the connection limit is *One*, the number of connections that can be established through a node is $n-1$, where n is the number of nodes in the network. For a limit of Two, it is $2(n-1)$ and so on. Varying the connection limit, we are restricting the number of connection establshed through a node, so that a node will not be overutilised.

A: Energy consumption

It measures the average amount of energy consumed in transmitting and/or receiving the packet. The plot for energy consumption *vs.* CBR connection for 60, 80 and 100 nodes are shown in Figures 3.5, 3.6, and 3.7 respectively. It is observed from the Figures that the energy consumption is less, when the connection limit is *One*. As the connection limit increases, energy consumption also increases. This increase is due to flooding of more RREQ packets.

Table 3.1: Simulation Parameters

Simulator	Qualnet 4.5
Simulation Time	120 Minutes
Terrain-Dimension	1500 * 1500 m^2
Traffic type	CBR
Mobility model	Random Waypoint
Speed	0 - 10 m/s
Pause time	30 second
Radio type	802.11b
Propagation limit	-111 dBm
Receiver sencitivity	-89
Data rate	2 Mbps
Packet size	512 bytes
Battery model	Simple linear coulombs count
Initial battery capacity	300 mAh
Waiting time at destination	200 ms

B: Network lifetime

We defined the network lifetime as the duration of network operation until the first node fails due to depletion of battery. The plot for network lifetime *vs.* CBR connections for 60, 80 and 100 nodes are shown in Figures 3.8, 3.9, and 3.10 respectively. From the above Figures it is observed that the network has a higher lifetime when the connection limit is set *One*. As the connection limit increases the network lifetime decreases. This is because some nodes are overutilized and they die quickly.

C: Packet delivery ratio

It is the ratio between the number of received data packets to the number of transmitted data packets. Figure 3.11, 3.12, and 3.13 shows the plots for packet delivery ratio *vs.* CBR connection at 60, 80, and 100 numbers of nodes respectively. From the above Figures it is observed that the packet delivery ratio decreases with increase in CBR connection. This is because, as the number of connection request

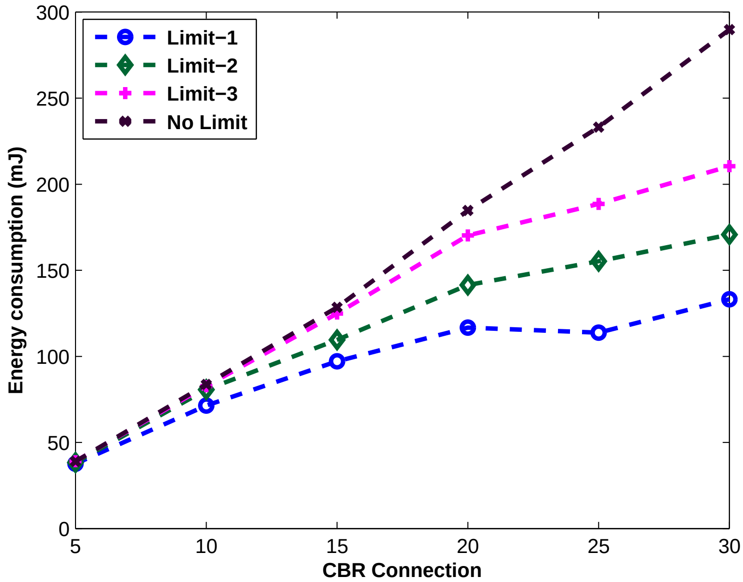


Figure 3.5: Energy consumption *vs.* CBR connection for 60 nodes.

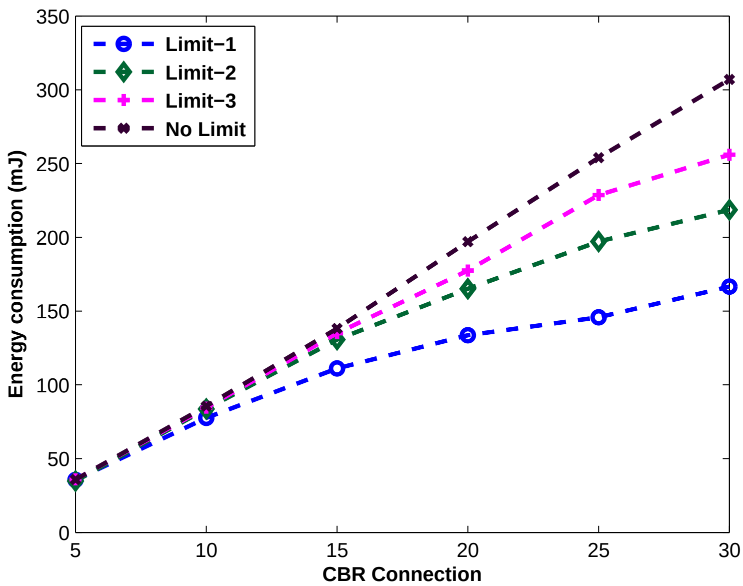


Figure 3.6: Energy consumption *vs.* CBR connection for 80 nodes.

increases, the number of RREQ packet flooded in the network also increases proportionately. Moreover, channel contention also increases. This consumes the available bandwidth, resulting into lower packet delivery ratio.

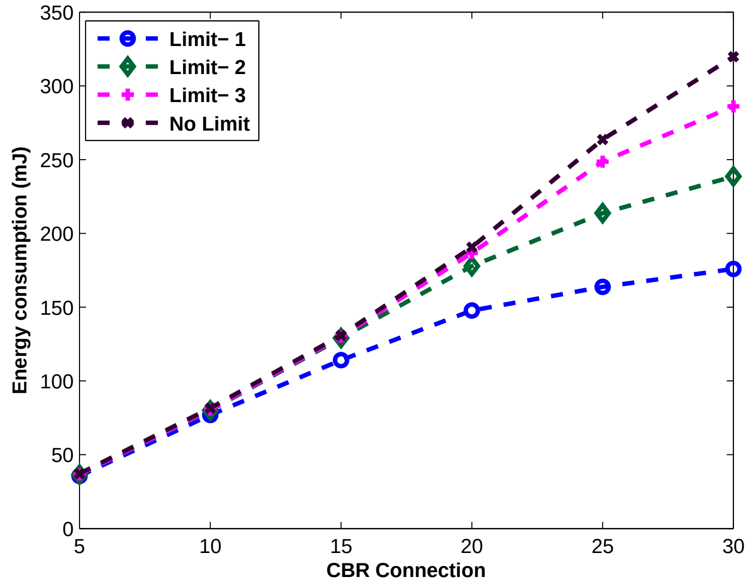


Figure 3.7: Energy consumption *vs.* CBR connection for 100 nodes.

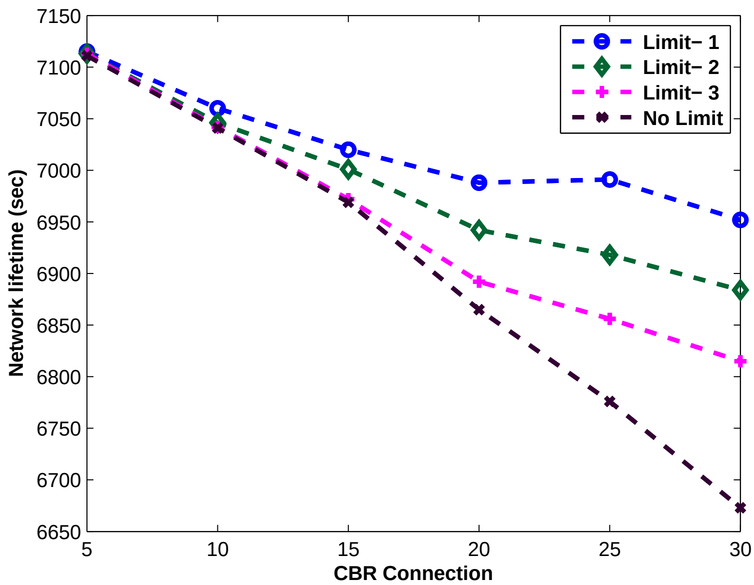


Figure 3.8: Network lifetime *vs.* CBR connection for 60 nodes.

From the above figures it is observed that the proposed scheme has lower energy consumption and higher network life at lower connection limit.

Next, we compare the proposed scheme with AODV [1] and LER [2]. The met-

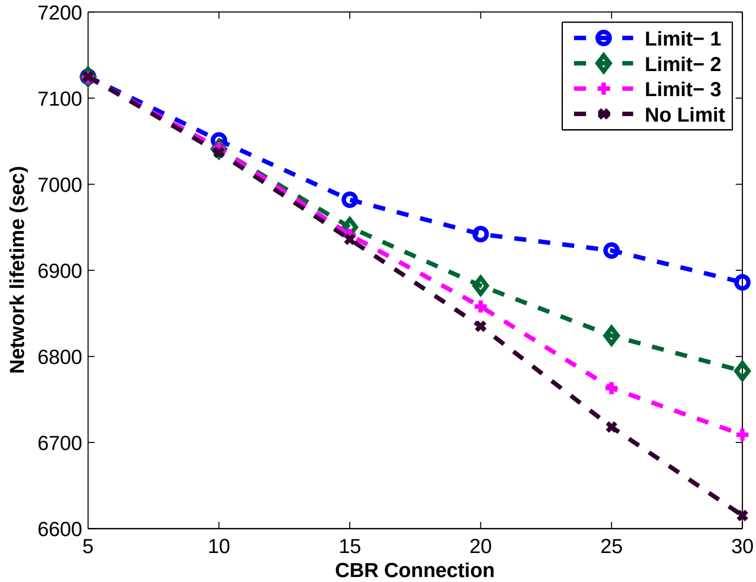


Figure 3.9: Network lifetime *vs.* CBR connection for 80 nodes.

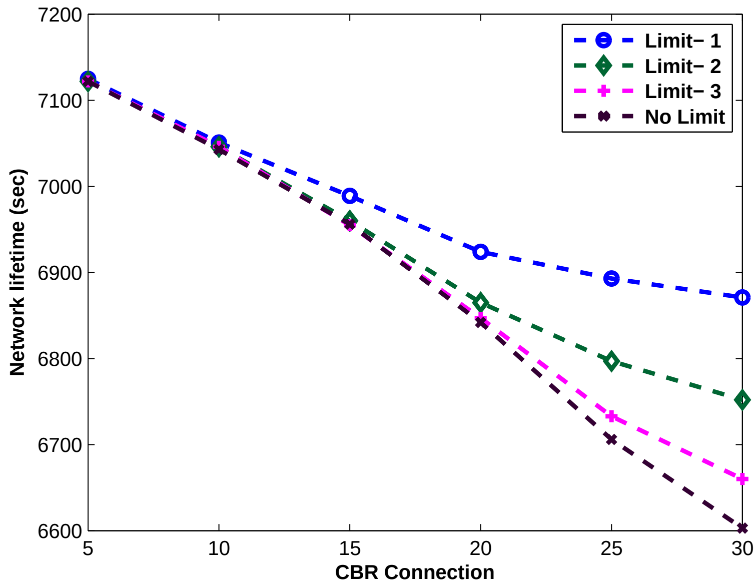


Figure 3.10: Network lifetime *vs.* CBR connection for 100 nodes.

rics considered for comparision are: *energy consumption, network lifetime, packet delivery ratio, end-to-end delay*, and *flooding of RREQ message.*

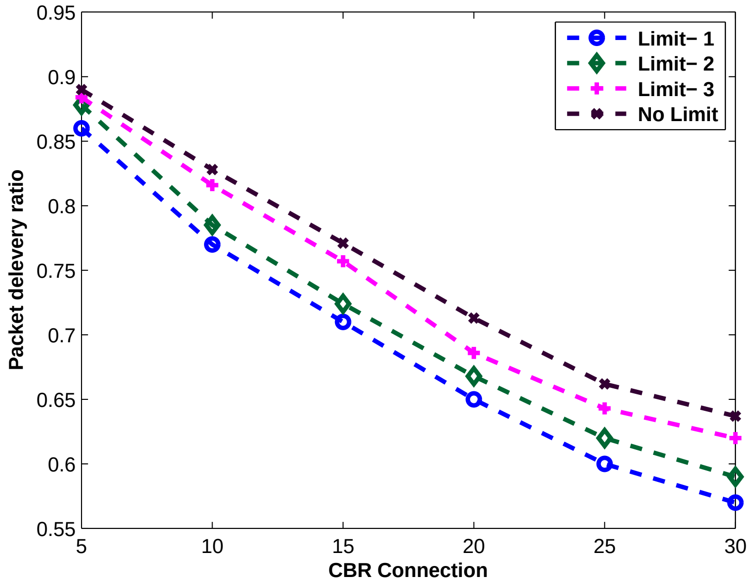


Figure 3.11: Packet delivery ratio *vs.* CBR connection for 60 nodes.

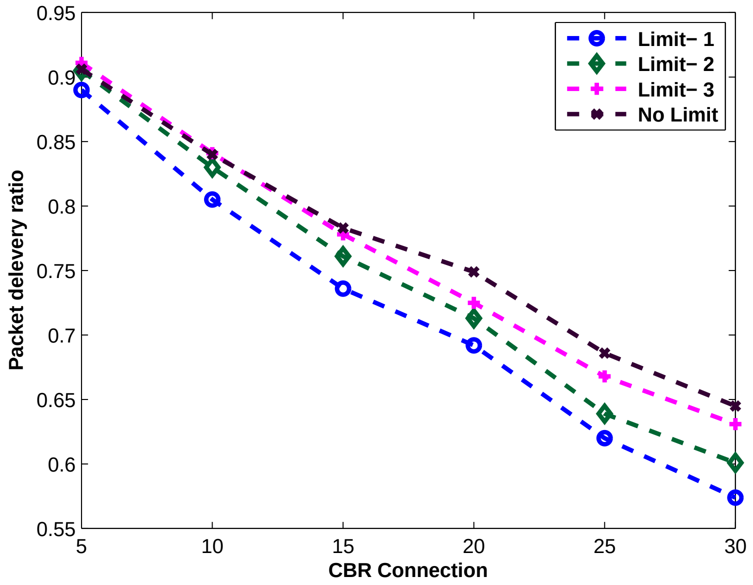


Figure 3.12: Packet delivery ratio *vs.* CBR connection for 80 nodes.

D: Comparison for energy consumption

The plots for energy consumption *vs.* CBR connection varying the number of nodes

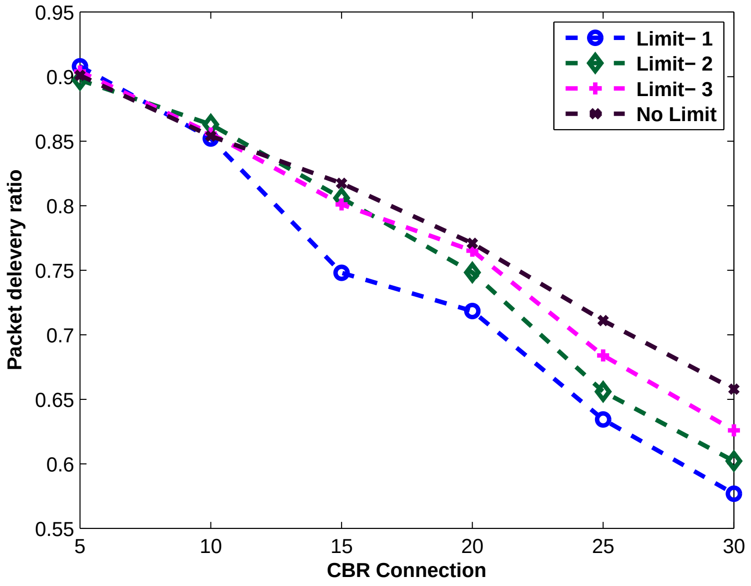


Figure 3.13: Packet delivery ratio *vs.* CBR connection for 100 nodes.

to 60, 80, and 100 are shown in Figures 3.14, 3.15, and 3.16 respectively. It is observed from the Figures that proposed scheme has lower overall energy consumption compared to AODV and LER. The lower energy consumption is attributed to optimal path selection process, application of power control approach, and reduction in the number of flooded RREQ message.

E: Comparison for network lifetime

The plot for network lifetime *vs.* CBR connection for 60, 80 and 100 numbers of node are shown in Figure 3.17, 3.18, and 3.19 respectively. From the above Figures it is observed that the proposed mechanism has higher network lifetime compared to AODV and LER. This is due to the fact that in the proposed technique a path is selected based on the energy consumption rate at each node. Further, it attempts to minimize the overutilization of a node and uses variable transmission power for data transmission.

F: Comparison for packet delivery ratio

Figures 3.20, 3.21, and 3.22 shows the plots for packet delivery ratio *vs.* CBR connection for 60, 80, and 100 numbers of nodes respectively. From the above Figures it is observed that the packet delivery ratio is higher at lower CBR connection and

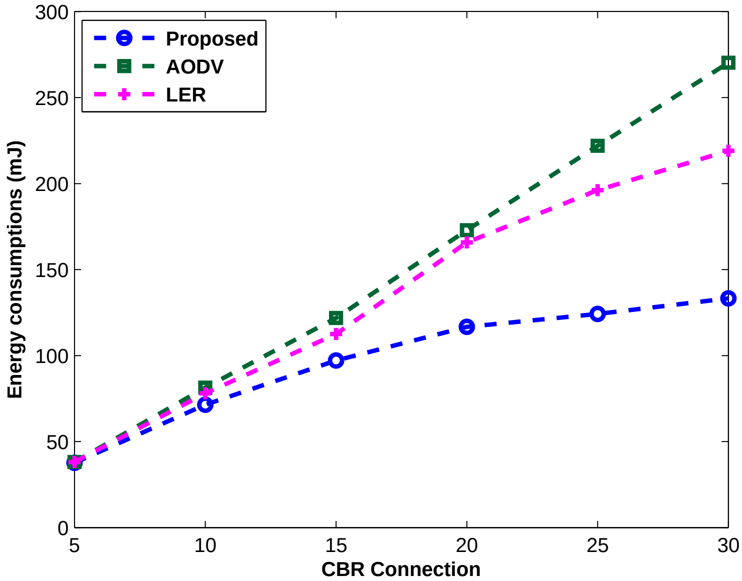


Figure 3.14: Comparison of Energy consumption *vs.* CBR connection for 60 nodes.

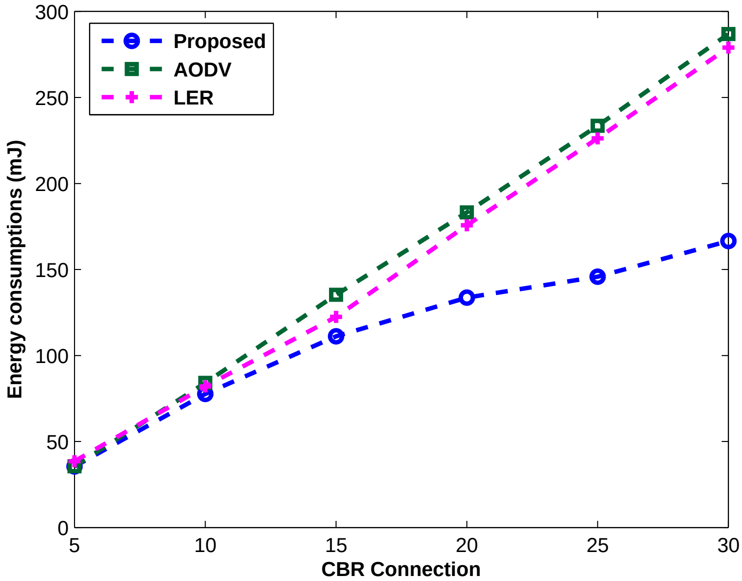


Figure 3.15: Comparison of Energy consumption *vs.* CBR connection for 80 nodes.

decreases gracefully with an increase in CBR connection. This is consistent with a published report, *"there is a price to pay in terms of throughput when optimizing energy"* [83].

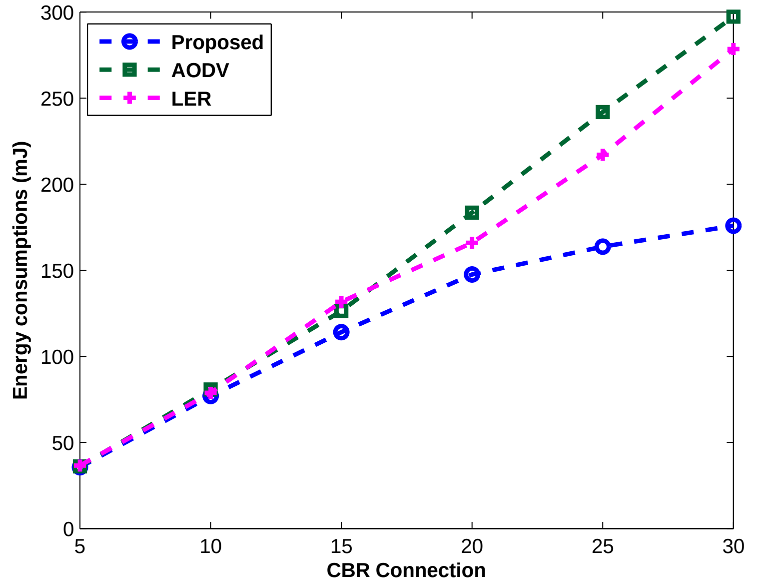


Figure 3.16: Comparison of Energy consumption *vs.* CBR connection for 100 nodes.

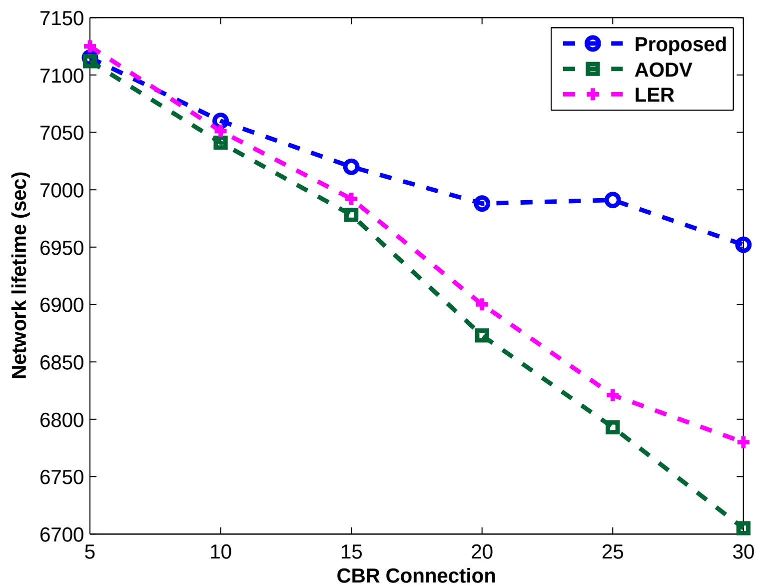


Figure 3.17: Comparison of Network lifetime *vs.* CBR connection for 60 nodes.

G: Comparison for average end-to-end delay

The plot for average end-to-end delay *vs.* CBR connection for 60, 80, and 100 nodes

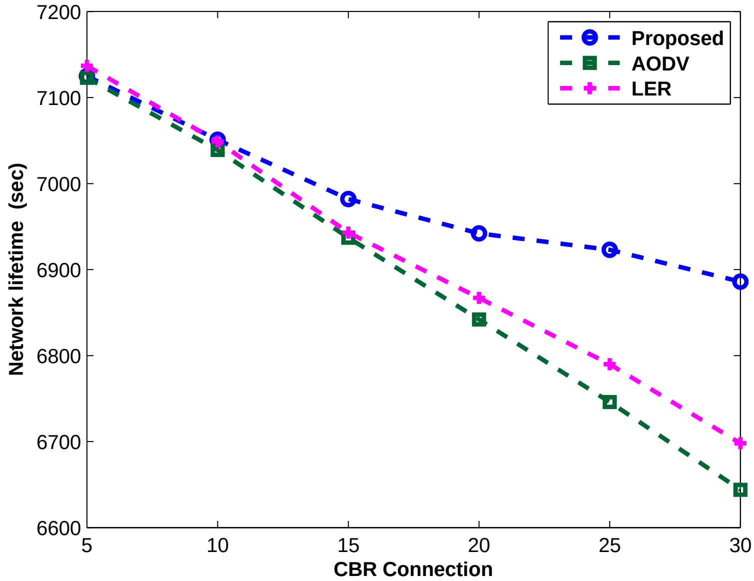


Figure 3.18: Comparison of Network lifetime *vs.* CBR connection for 80 nodes.

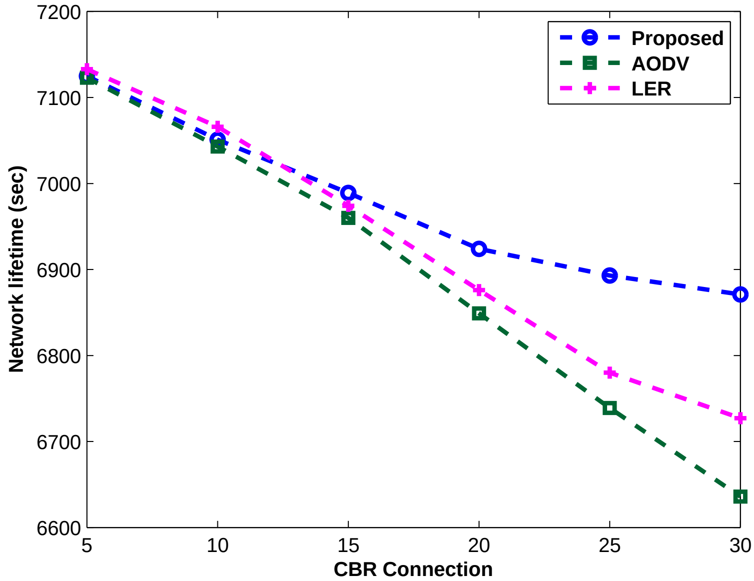


Figure 3.19: Comparison of Network lifetime *vs.* CBR connection for 100 nodes.

is shown in Figures 3.23, 3.24 and 3.25 respectively. It is observed from the above Figures that the average end-to-end delay increases with increase in the number of connections. This is consistent with the published report *"increased energy savings*

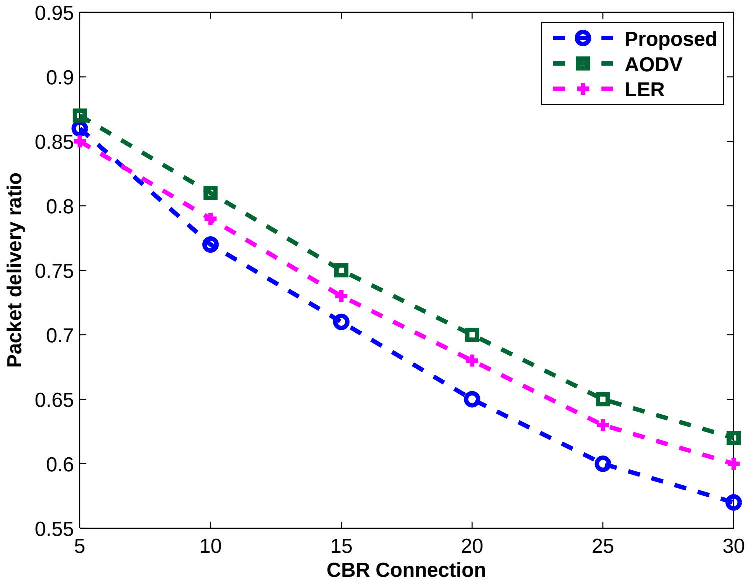


Figure 3.20: Comparison of Packet delivery ratio *vs.* CBR connection for 60 nodes.

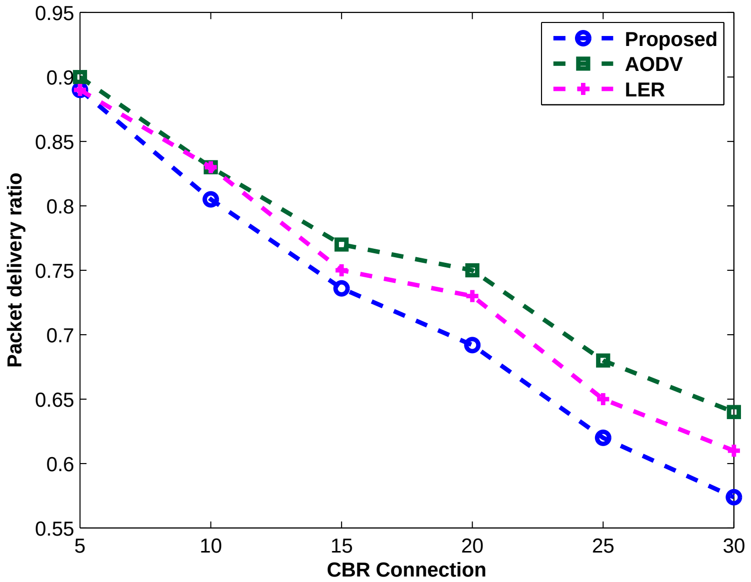


Figure 3.21: Comparison of Packet delivery ratio *vs.* CBR connection for 80 nodes.

come with a penalty of increased delay" [84].

H: Comparison for RREQ packet flooded

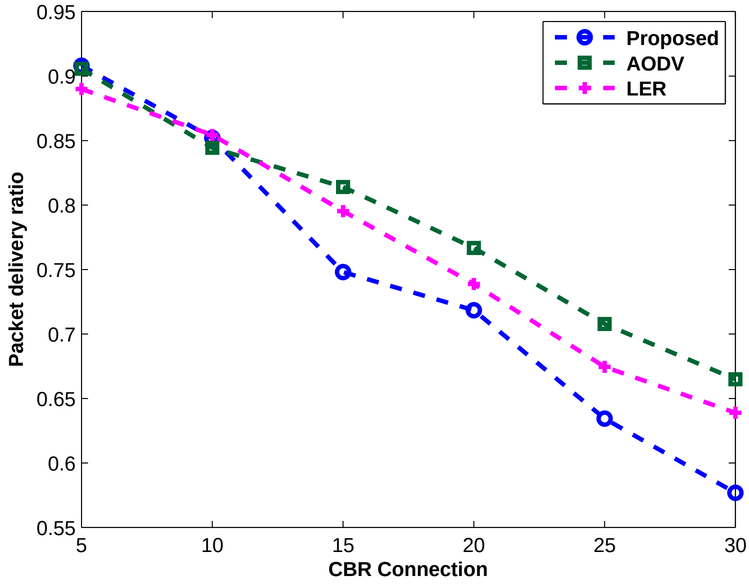


Figure 3.22: Comparison of Packet delivery ratio *vs.* CBR connection for 100 nodes.

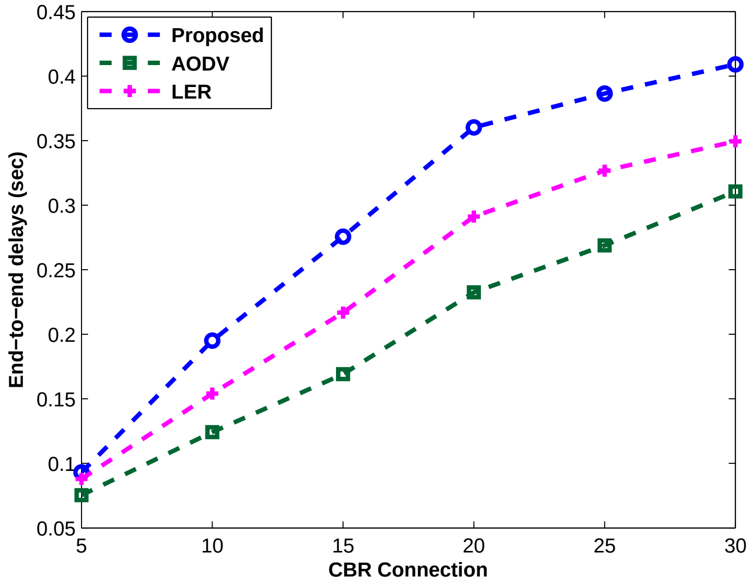


Figure 3.23: Comparison of End-to-end delay *vs.* CBR connection for 60 nodes.

The plots for number for RREQ packet flooded in the network *vs.* CBR connection varying the number of nodes to 60, 80 and 100 is shown in Figures 3.26, 3.27, and 3.28 respectively. From the above Figures it is observed that the number

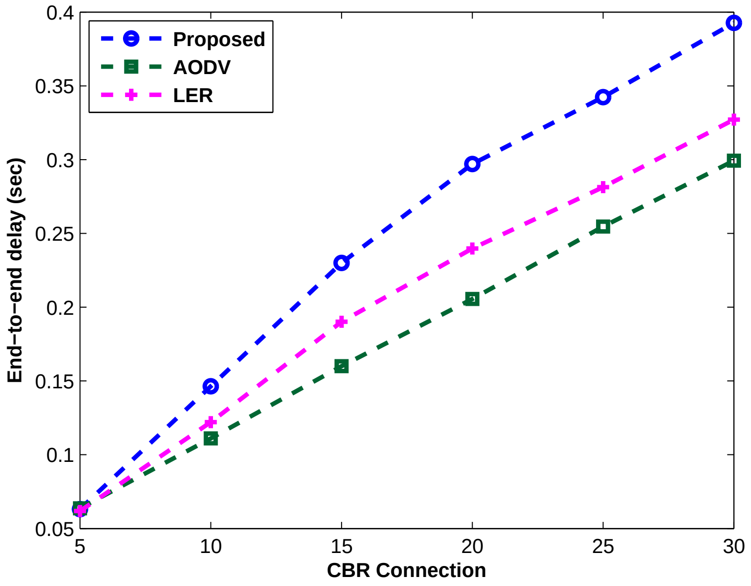


Figure 3.24: Comparison of End-to-end delay *vs.* CBR connection for 80 nodes.

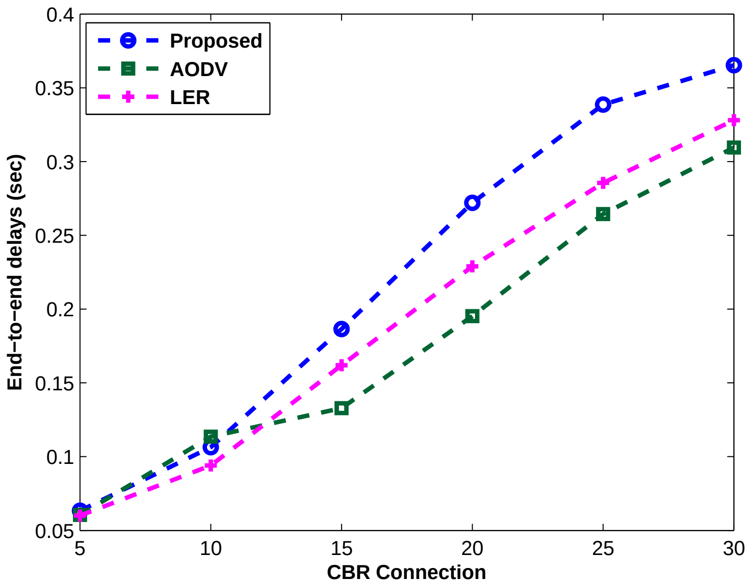


Figure 3.25: Comparison of End-to-end delay *vs.* CBR connection for 100 nodes.

of RREQ packet flooded in the network increases almost linearly with increase in the CBR connection for AODV and LER. However, in the proposed scheme it increases marginally with the number of CBR connection. This is because an upper bound on the number of connections that can be established through each node to a destination is fixed. A node forwards the RREQ until the limit is reached, and ceases to forward RREQ packet once the limit is reached.

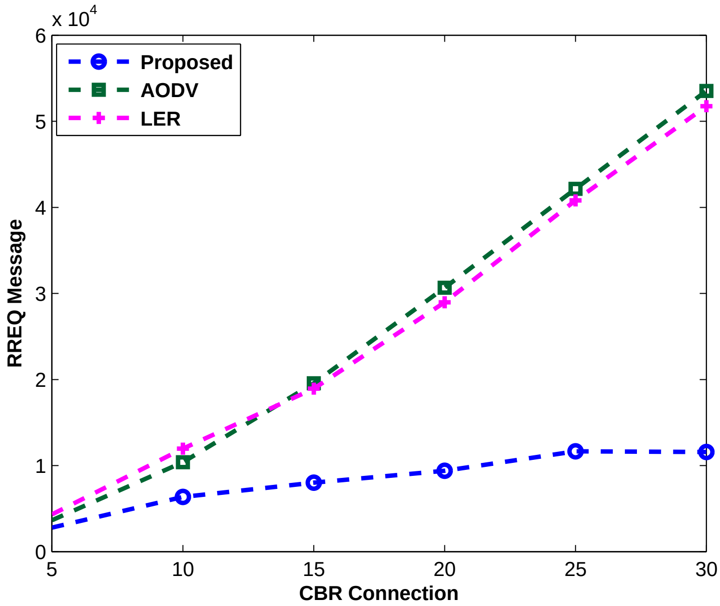


Figure 3.26: Comparison of Number of RREQ message *vs.* CBR connection for 60 nodes.

3.4 Summary

In this chapter, we proposed a cost metric to compute the lifetime of nodes in MANETs. The proposed cost metric is a function of residual battery power and energy consumption rate of participating nodes. Power control technique is used to minimize the energy consumption in the network. Nodes adaptively adjust their transmission power based on the location information of the next-hop node. We compared the proposed scheme with AODV and LER. It is observed that the proposed scheme has longer network lifetime and lesser energy consumption at the expense of lower packet delivery ratio and higher end-to-end delay.

In the next chapter, we propose a hybrid protocol for energy conservation in MANETs.

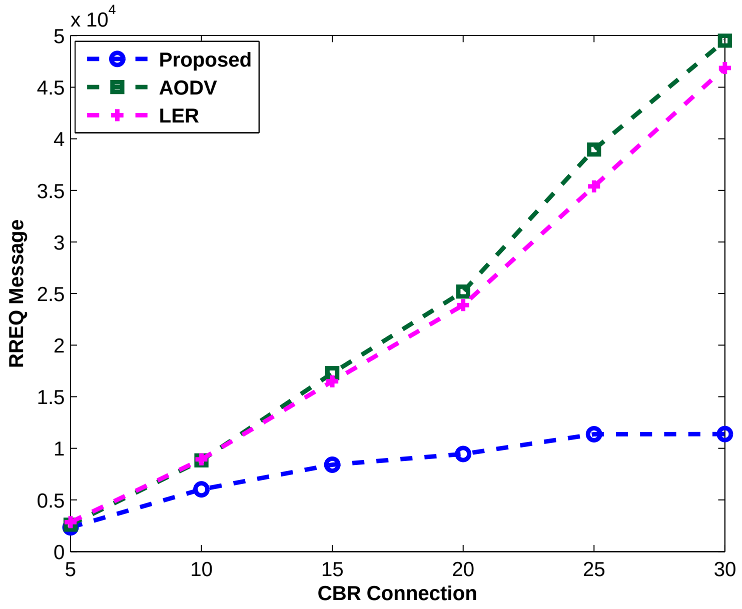


Figure 3.27: Comparison of Number of RREQ message *vs.* CBR connection for 80 nodes.

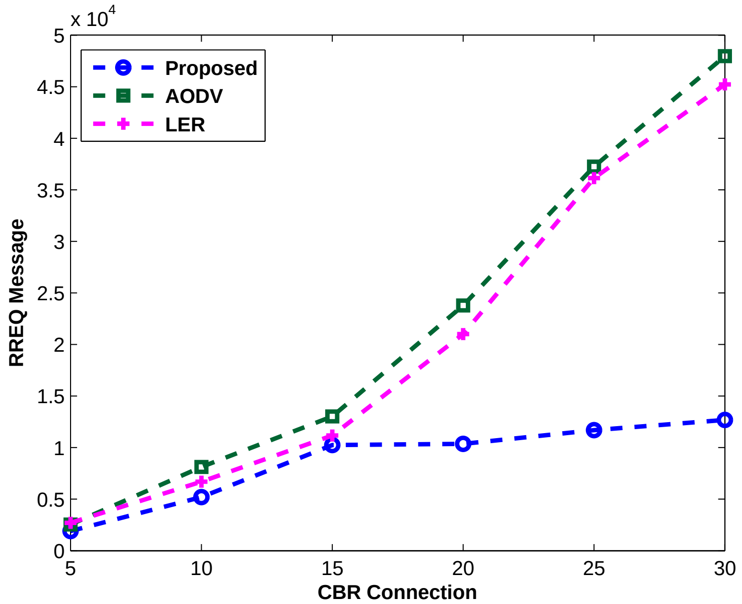


Figure 3.28: Comparison of Number of RREQ message *vs.* CBR connection for 100 nodes.

Chapter 4

LBTC: A Hybrid Energy Efficient Protocol for MANET

4.1 Introduction

Nodes in MANET usually transmit packets with maximum power. A packet transmitted with maximum power may reach the destination with lesser number of hops but can decrease the channel utilization and the remaining energy of nodes to a greater extent. This is because a node expends more energy, and the interference level increases when transmitted with maximum power. Energy can be saved by adjusting the node's transmission power to a lower level [92–94]. In recent years, many techniques have been proposed to conserve energy in MANETs. Topology control approach is one among them. The primary objective of a topology control algorithm is to readjust the network topology by reducing the transmission power at node level, while maintaining the network connectivity. In other words, the objective of a topology control approach is to remove the energy inefficient links at the node level by reducing the transmission power. The primary design goal in topology control protocols is to minimize the maximum power of a node. The secondary design goals are to improve the network performance such as throughput and network lifetime.

Power management is another approach to save energy. In this approach, a node remains in one of the following three states: *(a) active*: participates in network activity by sending and/or receiving packets, *(b) idle*: waits for the traffic, and *(c) sleep*: switch OFF its radio transceiver for a particular period, and then wakes up at the end of the period. Among the above three states, one that consumes the least amount of energy is the sleep state. Therefore, power management based protocols attempt to put as many nodes as possible into sleep state to save energy. However, they are more prone to network disruption. This is because, as the nodes goes to sleep state, the connectivity may be lost. A few power management approaches are discussed in [50, 95–98].

In this chapter, we have proposed a hybrid energy efficient technique, where nodes are put into sleep state depending on their connectivity information. The proposed scheme inherits the merits of both topology control approach and power management approach. A node in the proposed scheme goes to sleep state only when its absence does not create a local partition in its neighborhood. Also the transmission power of a node is reduced to a lower level.

4.2 Protocol Description

We proposed a hybrid energy conservation technique called *Location Based Topology Control with Sleep Scheduling* (LBTC) for ad hoc networks. LBTC takes into the account the merits of both topology control and power management approach. It uses variable transmission power, like the topology control approach. Further, it puts a node to sleep state like the power management approach. A node in LBTC, goes to sleep state only when itself satisfies that its absence will not create a local partition in its neighborhood. Section 4.2.1 describes the network model and notations used. The proposed scheme is presented in Section 4.2.2 and analyzed in Section 4.2.3.

4.2.1 Network model and notations

Wireless ad hoc network is modeled as a graph G = (V, E), where V represents the set of nodes and E represents the set of edges. Network consists of n number of heterogeneous nodes randomly deployed in the network. Each node has a unique identity (ID), and is equipped with omni-directional antenna. It is assumed that nodes are location aware and can compute the relative distance to their neighboring nodes. Let $P_{max}(u)$ be the maximum transmission power, $P_{min}(u)$ be the minimum transmission power, and P_u be the transmission power of a node $u \in V$. Initially, nodes transmit with their maximum power. We have assumed that transmission power P_u can be adjusted between the maximum and minimum value, *i.e,* $P_{min}(u) \leq P_u \leq P_{max}(u)$. Let P_{uv} be the minimum transmission power required for node u to communicate with its adjacent node v; P_{uv} is computed as:

$P_{uv} = D^{\beta} + C$, where D is the Euclidean distance between u and v, β is the path loss exponent, where $2 \leq \beta \leq 4$, and C is a constant [99]. Let G = (V, E) be the initial topology of the network, and $G' = (V, E')$ be the resulting topology, after application of transmission power control mechanism at nodes. We have further assumed that links are symmetric and the power control technique is applied within the neighborhood of a node. We have used following notations in this chapter:

One-hop neighbor set of a node u denoted as N_u^1 is defined as the set of nodes that are reachable from node u, when transmitted with power P_u, $P_{min}(u) \leq P_u \leq P_{max}(u)$.

Two-hop neighbor set of node u is denoted as N_u^2, is defined as the set of nodes that have a direct link to the nodes in the set N_u^1. This is represented as:

$$N_u^2 = \bigcup_{x \in N_u^1} N_x^1$$

The *common node* between two adjacent nodes u and v is denoted as $ComNode$, are those nodes which are one-hop neighbors of both u and v.

$$ComNode = \left\{ i | i \in N_u^1 \cap N_v^1 \right\}$$

where N_u^1, N_v^1 are the one-hop neighbor set of node u and v respectively.

4.2.2 Location Based Topology Control with Sleep Scheduling

In this section, we explain the proposed LBTC scheme. It operates in two phases: First phase is called *link selection* phase and the second phase is called *sleep scheduling* phase. In the *link selection* phase a node determines its transmission power. In the *sleep scheduling* phase a node decides whether to go to sleep state or not depending on the present traffic conditions and neighborhood connectivity. A node goes to sleep state only when it satisfies that its neighbors are reachable from one another without its active participation.

Link Selection Phase

In this phase a node u determines its transmission power that is enough to reach any other nodes in the set N_u^1. Nodes periodically broadcast a *Hello* message containing the sender *ID* and location information of the sender with P_{max}. On receiving the $Hello$ message, a node computes the transmission power required to the sender of

Hello message and updates its *vicinity* table which is maintained at each node. The structure of the vicinity table is shown in Table 4.1. The meaning of each field in the vicinity table is explained below:

SenID: Identity of the sender of *Hello* message.

LocInfo: Location information of the sender of *Hello* message.

DirCost: Link cost between the current node and the sender of *Hello* message.

MinCost: Minimum link cost between the current node and the sender of *Hello* message. Current node is the node that is updating its vicinity table. Initially, the value in this field is set to that of *DirCost*. This value is updated when there exists a *common node i* between the current node and *SenID* such that the transmission from the current node to *SenID* through node i has lower transmission cost than the *DirCost*.

ComNode: This field records the common node through which there exists an energy efficient path between the current node and *SenID*. It is updated when there exists a *common node i* between u and v such that $P_{ui} + P_{iv} < P_{uv}$.

LinkType: Indicates whether the link between the current node and *SenID* is direct (one-hop) or indirect (more than one-hop). For direct, the entry is *Zero* else *One*.

Table 4.1: Structure of the Vicinity Table

SenID	**LocInfo**	**MinCost**	**ComNode**	**DirCost**	**LinkType**

Initially, the vicinity table is empty, and is updated when a node receives a *Hello* message from its neighbors. From the vicinity table, a node determines the common node between itself and each of the neighboring nodes. *LinkType* field is set to *One*, if there exists a common node. Then, the node determines its transmission power, which is maximum of the *MinCost* field for which *LinkType* is set to *Zero*.

We consider Figure 4.1 to illustrate the *Link Selection* phase. Let the current location of node **X** be (91, 61). Assume that node **X** has received a *Hello* message (Z, (101, 61)) from node **Z**; the co-ordinates (101, 61) is the current location of node **Z**. The vicinity table at node **X** is updated as shown in Table 4.2. Here, we have assumed that, initially vicinity table at node **X** is empty. The *DirCost* between node **X** and **Z**, is computed to be 101. We have assumed $\beta = 2$ and $C = 1$ in our computation. *DirCost* and *MinCost* field is set to 101 and the *LinkType* to *Zero*. *ComNode* is set to *Null* as no common node is found between **X** and **Z** at this stage.

Vicinity table of node **X** after receiving *Hello* message from all its neighbor

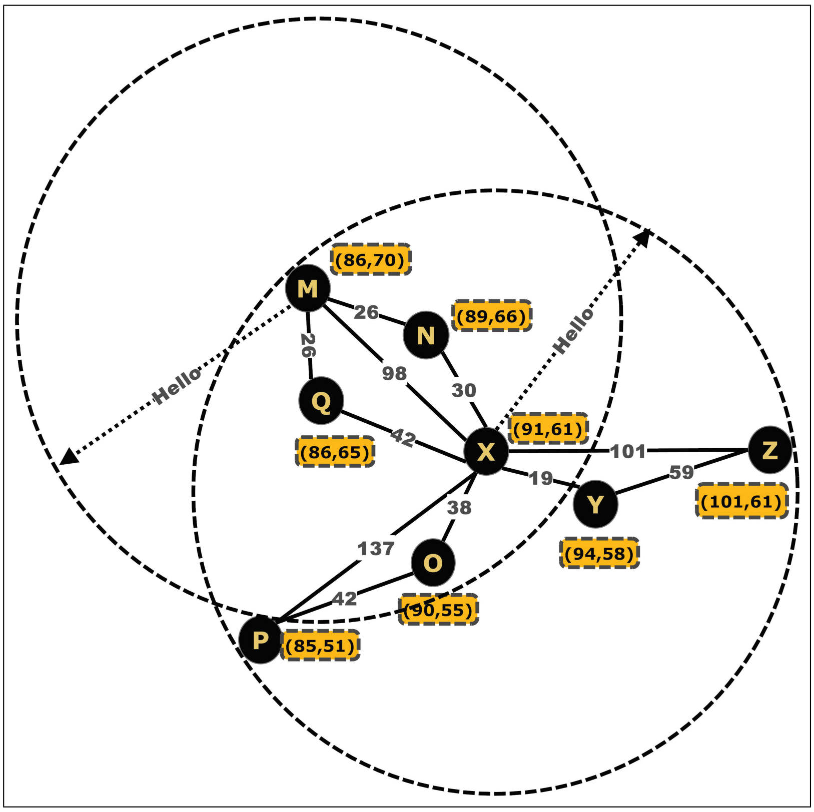


Figure 4.1: Nodes with location information.

Table 4.2: Node **X** Vicinity Table: After receiving *Hello* message from **Z**.

SenID	LocInfo	MinCost	ComNode	DirCost	LinkType
Z	(101, 61)	101	-	101	0

Table 4.3: Node **X** Vicinity Table: After receiving *Hello* message from neighbors.

SenID	LocInfo	MinCost	ComNode	DirCost	LinkType
Z	(101, 61)	101	-	101	0
Y	(94, 58)	19	-	19	0
M	(86, 70)	98	-	98	0
N	(89, 66)	30	-	30	0
P	(85,51)	137	-	137	0
O	(90,55)	38	-	38	0
Q	(86,65)	42	-	42	0

is shown in Table 4.3. After gathering information about its neighbor, node **X** determines whether there exist any *ComNode* between itself and its neighbors in the vicinity table. Node **Y, N**, and **O** are the *ComNode* between **X** and **Z**, **X** and **M**, and **X** and **P** respectively. There can be more than one node within the transmission range of a pair of nodes. Only that node is selected as the *ComNode* through which the cost between the pair of nodes is minimum. For example, node **N, O, P, Q** are within the transmission range of node **X** and **M**. But node **N** is selected as the *ComNode* between **X** and **M**. After obtaining the *ComNode*, node **X** update the *LinkType*, *ComNode* and *MinCost* field in its vicinity table. The updated vicinity table is shown in Table 4.4. From the table it is observed that the cost of transmitting from **X** to **Z** through node **Y** is 78, whereas the direct cost is 101. Similarly, the cost of transmitting from **X** to **P** through **O** is 80, whereas the direct cost is 137.

Table 4.4: Node **X** Vicinity Table: After determining the *ComNode*.

SenID	LocInfo	MinCost	ComNode	DirCost	LinkType
Z	(101, 61)	78	Y	101	1
Y	(94, 58)	19	-	19	0
M	(86, 70)	56	N	98	1
N	(89, 66)	30	-	30	0
P	(85,51)	80	O	137	1
O	(90,55)	38	-	38	0
Q	(86,65)	42	-	42	0

From the updated vicinity table, node **X** compute its transmission power. It consider only those nodes for which the *LinkType* field is set to *Zero*. Node **X**, considers the node **Y, N, O** and **Q** as the *LinkType* field to these nodes are set to *Zero*. Then, node **X** determine its transmission power, which is the maximum value in the *DirCost* field of node **Y, N, O,** and **Q** *i.e*, *max(19, 30, 38, 42) = 42*. The resulting topology as seen by node **X** after the *Link selection* phase is shown in Figure 4.2. It is observed from the Figure 4.2 that node **X** has lesser number of one-hop neighbors than before shown in Figure 4.1.

Sleep Scheduling Phase

In this phase a node decides, whether to enter into sleep state or not, depending on the traffic pattern and neighborhood connectivity information. A node remains in one of the following three states: *(i)* Active, *(ii)* Watch, and *(iii)* Sleep. Initialy, a node remain in *active* state. In *active* state, nodes participate in data communication and periodically broadcast a *Hello* message. After the expiry of *Hello* message

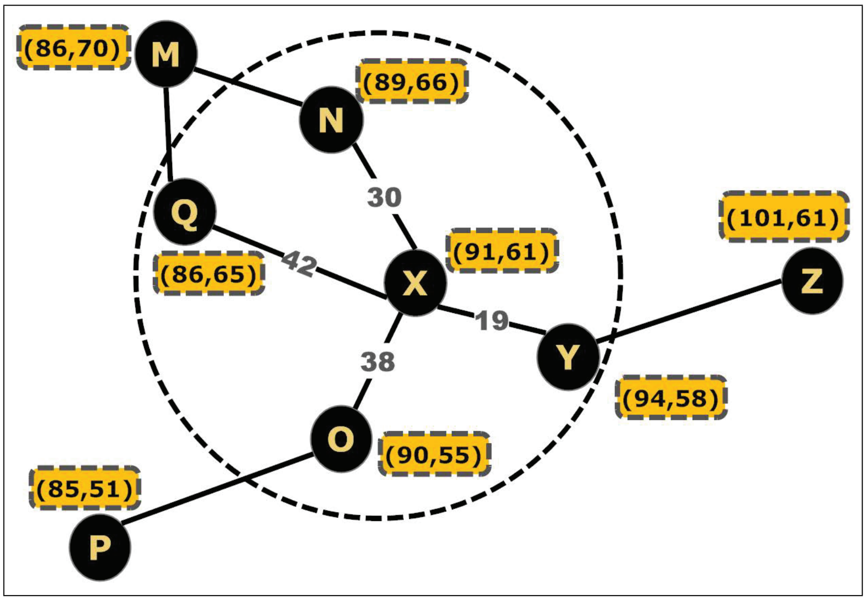


Figure 4.2: Resulting topology as seen by node **X** after link selection phase.

period, T_H, a node enters into a *watch* state. In *watch* state, a node decides whether to go to *active* state or to *sleep* state. In *active* and *watch* state the radio transceiver of a node is turned ON, whereas it is turned OFF in *sleep* state. A node in sleep state wakes up at the end of sleep time, T_S, and enters into *watch* state. The state transition diagram is shown in Figure 4.3.

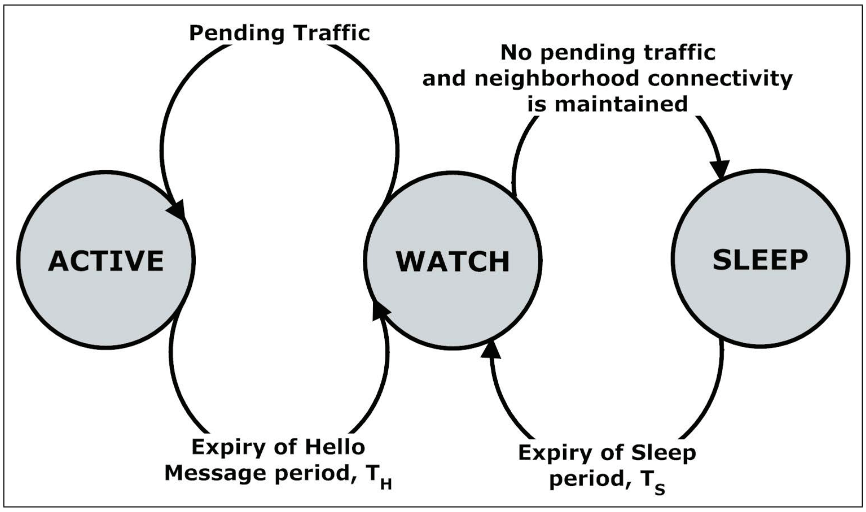


Figure 4.3: State transition in LBTC.

When a node goes to sleep state it may create a local partition, within its neighborhood. For example, a critical node on a path, when goes to sleep state, creates a local partition. This is because when a critical node goes to sleep state, all paths through that node are broken, and any ongoing traffic through that node gets disturbed. Therefore, before going to sleep state, a node should check, whether its absence will create any local partition. In the *watch* state a node check for local partition. If the node has no traffic to participate and its absence doesn't create a local partition, then the node goes to sleep sate.

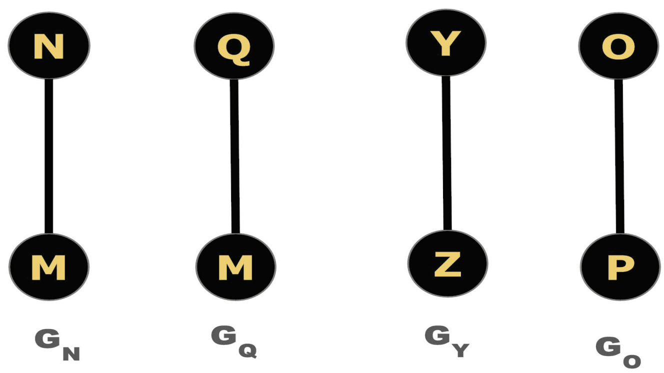
To determine the sleep eligibility, a node u performs the following. It constructs subgraphs G_i for every node $i \in N_u^1$. This is constructed from the two-hop neighbor set of node u, i.e N_u^2. The vertex in the subgraphs G_i are the one-hop neighbors of node i, excluding node u. Above subgraphs are merged to form a larger subgraph. In the merge operation two subgraphs say G_k and G_l can be merged if $\exists x | x \in G_k \cap G_l$. That is two subgraphs are merged to form a larger subgraph only if there exists a node common to both the subgraphs.

If the resulting subgraph after the merge operation, is a single subgraph, then node u enters to sleep state. Otherwise, node u remains in the active state. The *sleep eligibility* algorithm is given in Algorithm 1.

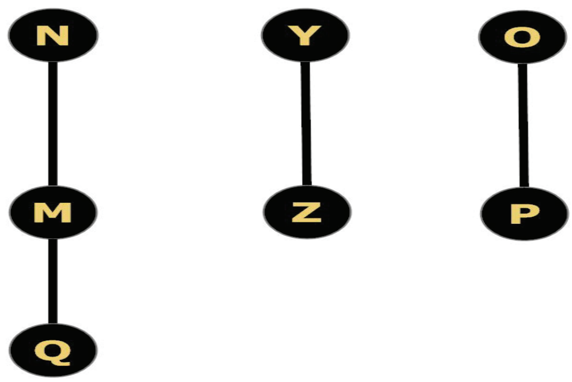
Algorithm 1 : Sleep Eligibility Algorithm

1: Let the algorithm be executed at node u
2: S_G: Is the set of nodes, such that any two nodes in the set is either directly connected or through other nodes in the set S_G. Initially the set S_G is empty.
3: PN_i: Set of neighbors of node i, for $i \in N_u^1$. The node i is not included in the set PN_i.
4: **Repeat** Step 5–10 **Until** no further elements can be added to S_G.
5: **for** $\forall\ PN_k \mid k \in N_u^1$ **do**
6:     **if** $(\exists y \in PN_k\ and\ y \in S_G)$ **then**
7:         $S_G = S_G \cup PN_k$
8:         Discard PN_k for further consideration
9:     **end if**
10: **end for**
11: **if** $(z \in S_G,\ \forall z \in N_u^1)$ **then**
12:     node u goes to sleep state
13:     **else**
14:     node u goes to active state
15: **end if**

We consider Figure 4.2 to illustrate the sleep eligibility. For illustration purpose, we have assumed that the Figure 4.2 is the resulting topology, after all nodes have executed the link selection phase. Let node **X** is in the watch state and executes the sleep eligibility algorithm. Figure 4.4(a) shows the subgraph before the merge operation and Figure 4.4(b) shows all the subgraphs after the merge operation. Since the subgraphs can not be merged to form a single subgraph, node **X** transit to active state from watch state.



(a) Before the merge operation



(b) After the merge operation

Figure 4.4: Subgraph before and after merge operation.

4.2.3 Analysis

In this sub-section, we analyze the network connectivity in the proposed LBTC scheme.

Theorem: If two nodes are connected before the *link selection* phase, then they are also connected after the *link selection* phase.

Proof: Let G = (V, E) be the network topology before the *link selection* phase and $G' = (V, E')$ be the network topology after the *link selection* phase. We have to show that for any u, $v \in V$, if there exists a path in G, then there also exists a path from u to v in G'.

Since G is connected, for any u, $v \in V$, there exists a path from u to v in G. Let the path be $u \stackrel{k}{\rightarrow} v$, where k is the number of links on the path from u to v. We show by means of induction that there also exists a path from u to v *i.e*, $u \stackrel{k'}{\rightarrow} v$ with $k' \geq k$ is the number of links on the path from u to v in G'.

We use induction hypothesis to prove the above stated theorem.
Let $k = 1$, which means that node v is within the transmission range of node u in G. In G', v will be either in one-hop or two-hop neighbor of u. Therefore, a path from u to v exists in G'.

Let us assume that it is true for $k = n$, *i.e*, there exists a path in G from u to v with n number of links. Therefore, there also exist a path from u to v in G', and the number of links in the path is greater than or equal to n.
Let $k = n + 1$, then the path from u to v with $n + 1$ number of links in G is shown below in Figure 4.5.

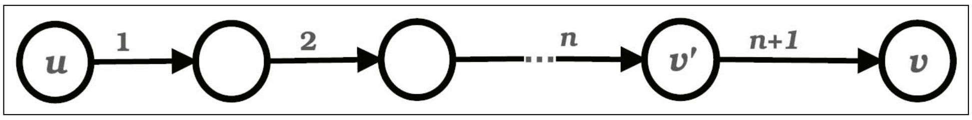


Figure 4.5: Exemplary network.

The above path can be interpreted as two sub-paths one from u to v' with n number of links and the other from v' to v with single link in G. From the induction hypothesis, we know that if there exists a path from u to v' in G with n links then there also exist a path from u to v' in G'. From the basis, we know that if there exists a path from v' to v with single link in G then there exists a path from v' to v in G'. Hence, there exists a path from u to v in G'. Therefore, if G is connected then G' is also connected. (Proved)

4.3 Simulation Results

We simulated the proposed LBTC technique using QualNet 4.5 [24] simulator. The parameters considered for simulation are shown in Table 4.5.

Table 4.5: Simulation Parameters

Simulator	Qualnet 4.5
Terrain dimension	1500 * 1500 m^2
Simulation Time	120 Minutes
Node speed	0-10 m/s
Traffic type	CBR
Routing protocol	AODV
Mobility model	Random Waypoint
Propagation limit	- 111 dBm
Receiver sensitivity	-89
Transmit power	600 mW
Receive power	450 mW
Data rates	2 Mbps
Radio model	802.11b
Packets size	512 bytes
Initial battery capacity	300 mAh

We compared LBTC with two existing protocols: LFTC [3] and ANTC [4]. The metrics considered for comparison are: Energy conservation, Network lifetime, Throughput, and End-to-end delay.

A: Energy consumption

Energy consumption determines the effectiveness of an energy saving scheme. We consider the energy model in [29] for measuring the energy consumption. The plot for energy consumption *vs.* CBR connection, number of node, and pause time is given in Figures 4.6, 4.7, and 4.8 respectively. It is observed from the above Figures that LBTC has lower energy consumption. This is because in LBTC, energy efficient links are selected, and nodes are put to sleep state if they do not actively participate in the ongoing transmission.

B: Network lifetime

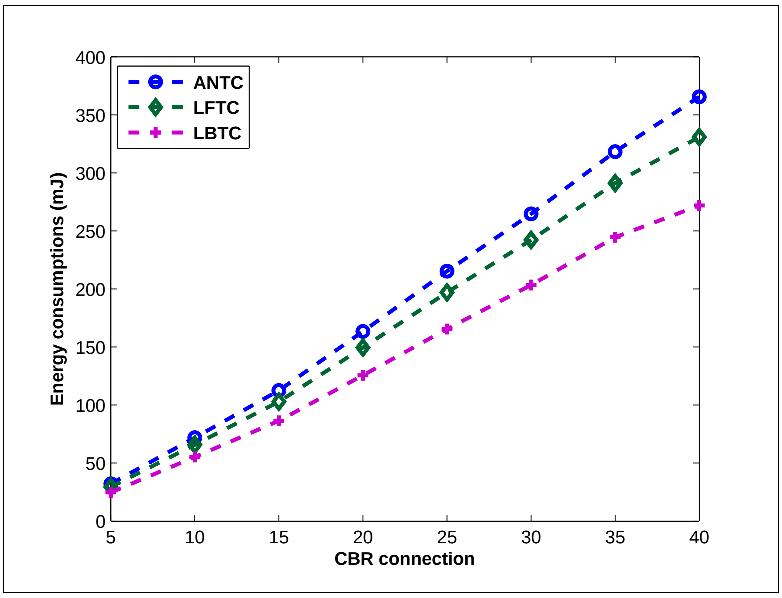


Figure 4.6: Energy consumption *vs.* CBR connection for 70 nodes.

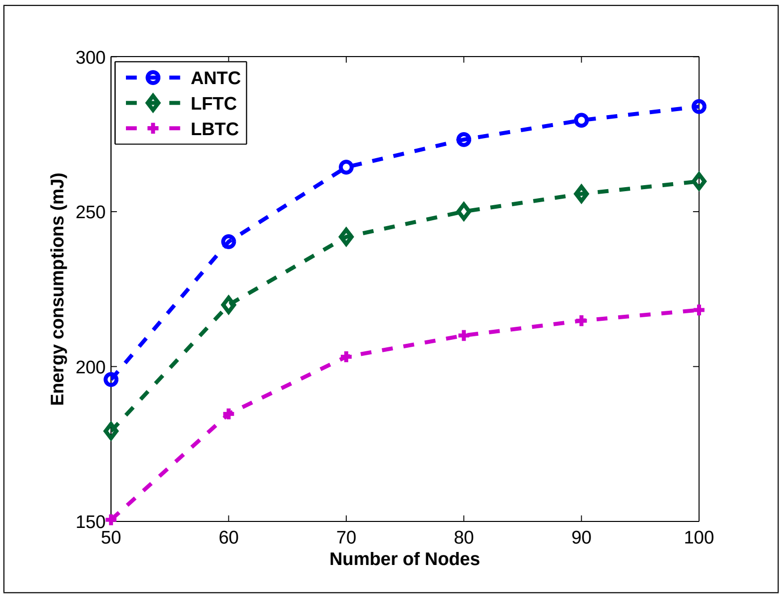


Figure 4.7: Energy consumption *vs.* Number of nodes for 25 CBR connection

The plot for network lifetime *vs.* CBR connection, number of node, and pause time is shown in Figures 4.9, 4.10, and 4.11 respectively. It is observed from the above Figures that, LBTC has higher network lifetime. This is because of lower energy consumption.

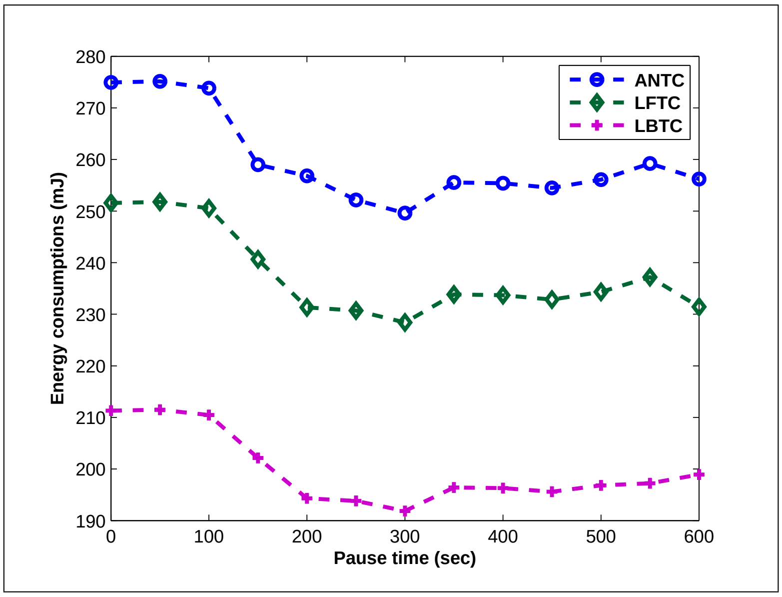


Figure 4.8: Energy consumption *vs.* Pause time for 70 nodes and 25 CBR connection

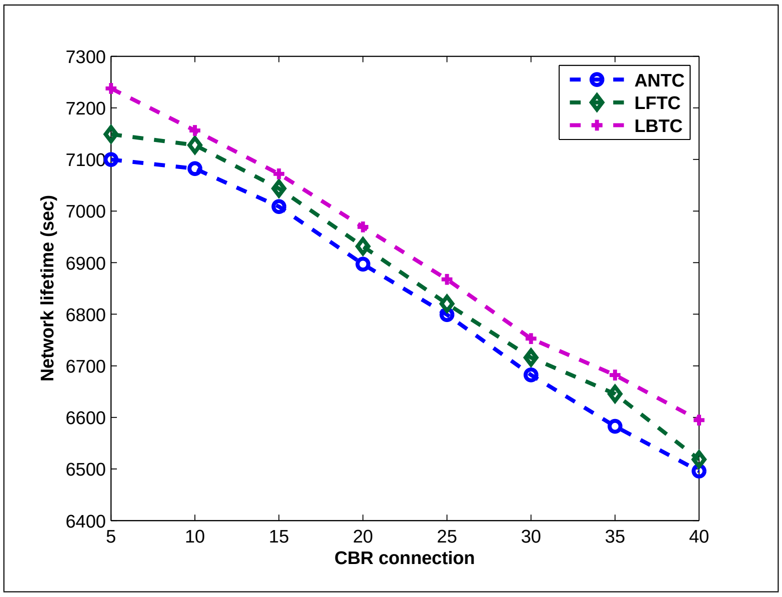


Figure 4.9: Network lifetime *vs.* CBR connection 70 nodes.

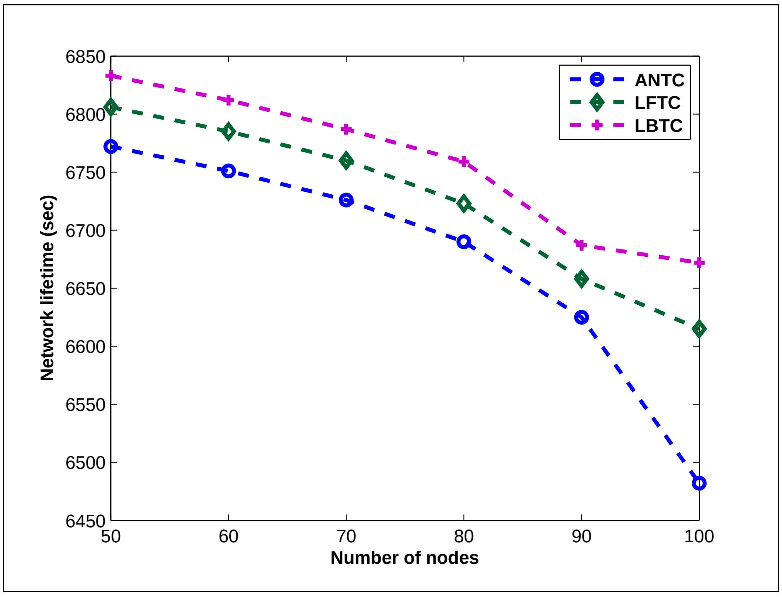


Figure 4.10: Network lifetime *vs.* Number of nodes for 25 CBR connection.

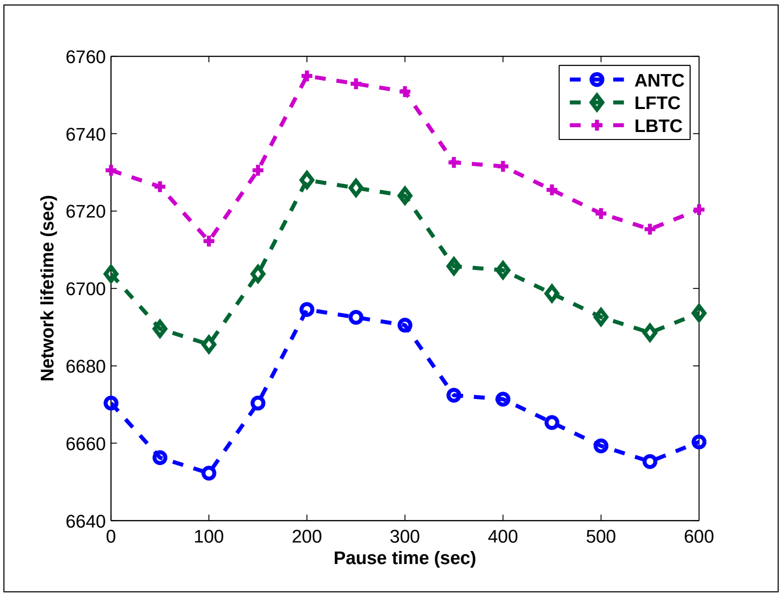


Figure 4.11: Network lifetime *vs.* Pause time for 70 nodes and 25 CBR connection.

C: Throughput

We plot the throughput *vs.* CBR connection, pause time, number of node in Figures 4.12, 4.13, and 4.14 respectively. From the above Figures, it is observed that a higher throughput is attainable in LBTC. Higher throughput is attributed to increase in longevity of the network due to proper adjustment of transmission power in the *link selection* phase, and energy saving in the *sleep scheduling* phase.

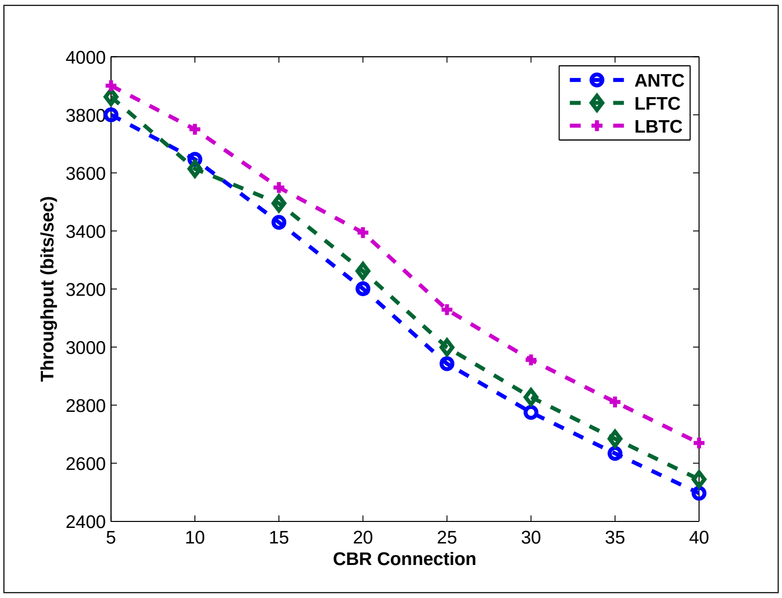


Figure 4.12: Throughput *vs.* CBR connection for 70 nodes.

D: End-to-End delay

The plot for end-to-end delay *vs.* CBR connection, number of node, and pause time is shown in Figure 4.15, 4.16, and 4.17 respectively. From the above Figures, it is observed that LBTC has higher end-to-end delay as compared to LFTC and ANTC. This is due to the increase in the number hop count as nodes transmit with lower power. This observation is consistent with the published report that the average end-to-end delay increases when the transmission power control mechanism is applied [100].

4.4 Summary

In this chapter, we proposed a hybrid energy efficient protocol called *LBTC* for ad hoc networks. The proposed mechanism considers the merits of both topol-

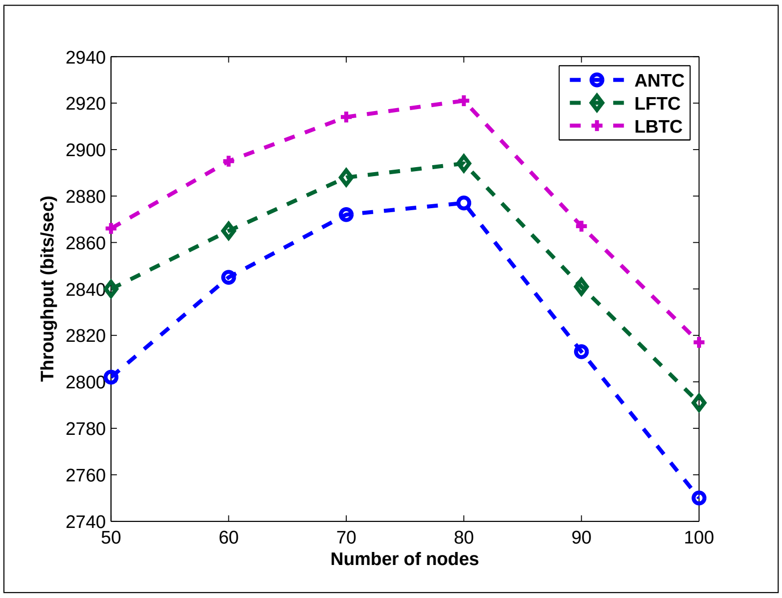


Figure 4.13: Throughput *vs.* Number of nodes for 25 CBR connection.

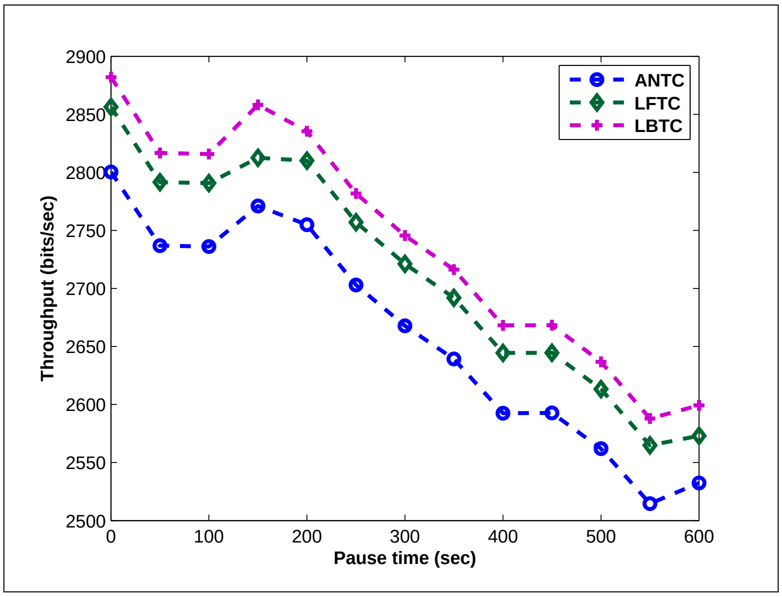


Figure 4.14: Throughput *vs.* Pause time for 70 nodes and 25 CBR connection.

ogy control scheme and power management scheme. LBTC selects energy efficient links and the nodes which do not actively participate in communication are put to sleep state. We have compared LBTC with two existing schemes. It is observed that LBTC is more energy efficient and delivers higher throughput at the cost of end-to-end delay. In the next chapter, we proposed a framework for post-disaster

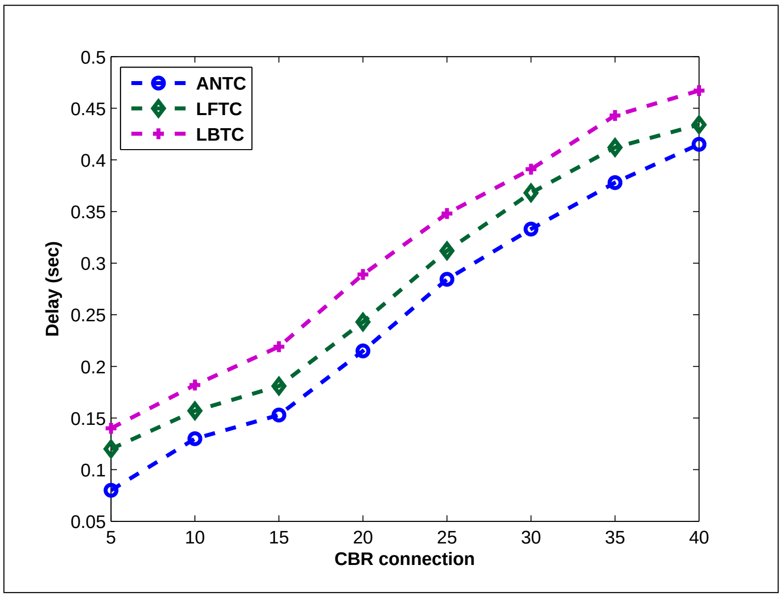


Figure 4.15: Average end-to-end delay *vs.* CBR connection for 70 nodes.

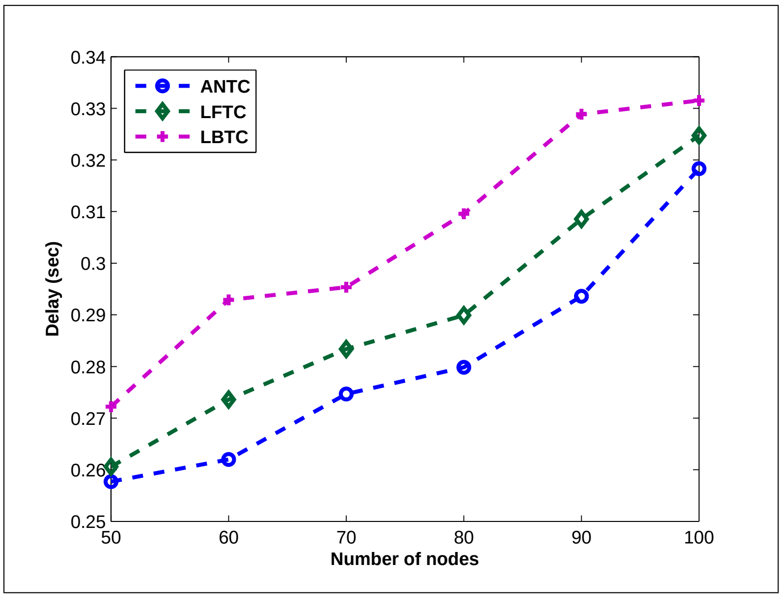


Figure 4.16: Average end-to-end delay *vs.* Number of nodes for 25 connection.

communication. In the proposed framework we made an attempt to reduce the end-to-end delay without compromising the network lifetime.

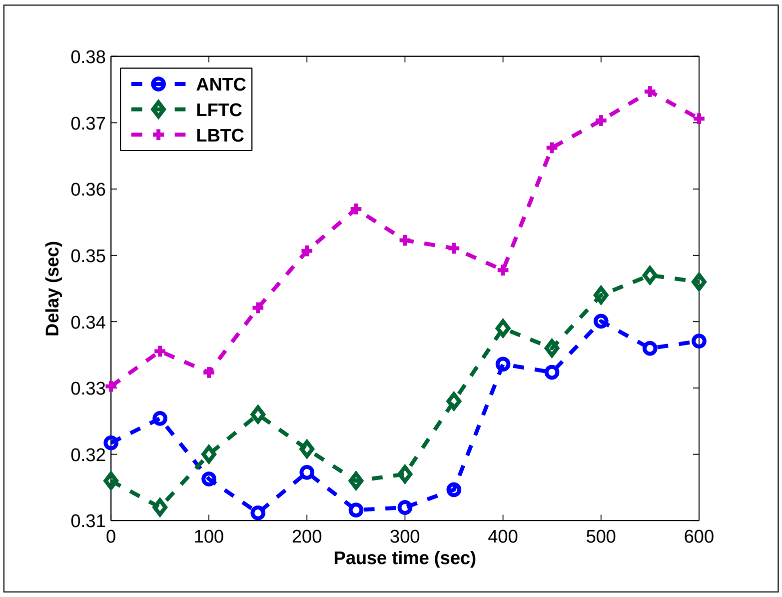


Figure 4.17: Average end-to-end delay *vs.* Pause time for 70 nodes and 25 CBR connection.

Chapter 5

A Framework for Post-Disaster Communication using MANET

5.1 Introduction

The hurricane Sandy in 2012, Tsunami in 2011, terrorist attack on World Trade Center in 2001, have drawn lots of attention to improve the rescue operation following a disaster. In the last few years, there have been significant improvement in the disaster management front, yet there exists enough scope for further improvement. The challenges in disaster management are:

(*i*) Disaster can not be predicted and its severity can not be measured in advance,

(*ii*) It strikes suddenly, and uproot the entire communication system. Without a reliable communication system it is difficult to carry out the rescue operation,

(*iii*) Use of radio communication is severely affected due to increase in network traffic. Network deployed at the disaster site may experience congestion due to massive exchange of voice and/or message. The entire region might suffer from degraded communication which affects the rescue operation. Message delivery gets delayed due to congestion.

As the infrastructure based network gets uprooted, wireless ad hoc networks can play a significant role in disaster mitigation [102–106]. It can be quickly deployed at the disaster affected site, and does not require any fixed networking infrastructure.

Wireless ad hoc networks designed for disaster mitigation, must provide robust ubiquitous communication, sufficient enough to support the geographical coverage and mobility requirement of the people involved in the rescue operation. However, the use of wireless ad hoc networks for disaster management faces the following challenges:

(*i*) Energy constraint: Nodes in wireless ad hoc networks have limited battery capacity, which must be judiciously used to increase the network lifetime. In a disaster scenario, networks should remain active as long as possible. To increase the network lifetime, attempt should be made to minimize the power consumption at nodes.

(*ii*) Network congestion: Traffic is likely to increase many folds aftermath of disaster. As a result, network gets congested, and collision takes place. Retransmission due to collision further aggravates the congestion. This decreases the network throughput and unnecessarily depletes energy at the node. For achieving higher throughput, congestion in the network has to be minimized.

(*iii*) End-to-end delay: Due to network congestion the end-to-end delay increases. For initiating prompt action, message should be timely delivered.

To address the above challenges, we propose a framework for disaster response using wireless ad hoc network. The main features of the framework includes:

(*i*) A multi-channel MAC protocol to achieve higher throughput, and minimize the impact of hidden and exposed terminals,

(*ii*) An energy efficient node-disjoint multi-path routing to enhance network lifetime, and

(*ii*) Distributed topology control mechanism to reduce the maximum transmission power at node level.

5.2 Disaster Response Model

Emergency response system uses various wireless technology such as cellular network, Wi-Fi, LR-WPANs (IEEE 802.15.4) [107], etc. Most of these technology operates in a client-server mode, and are fully dependent on the service provider such as base station and access points. Moreover, they are prone to congestion and failure of base station or access point degrades the system performance. To overcome the above limitations, a peer-to-peer architecture using wireless ad hoc network is adopted by the researchers. In this section, we discuss a few emergency response system using wireless ad hoc networks, as reported in the literature.

To maintain end-to-end route, some systems adopted decentralized peer-to-peer architecture and employed delay tolerant network (DTN). Such an architecture is *DistrenessNet* [25]. DistressNet is an ad hoc wireless architecture proposed for disaster response application. This includes a multipath routing with a multi-channel

MAC protocol. Nodes in DistressNet can determine their location, name and network address. It uses designated negotiators to manage schedule information and coordinate on behalf of individual nodes. Negotiators monitor a default channel continuously and coordinate agreements that allow nodes to communicate. DistrenessNet uses a multipath routing in which connected part of the network uses an on-demand routing protocol and is based on message prioritization.

A routing protocol for emergency communication is presented in [108]. Authors in this paper considered a hybrid network, consisting of both ad hoc, and cellular network to maintain connectivity between base station (BS) and nodes in a disaster affected area. In this hybrid network architecture, nodes communicate with the base station; but switches to ad hoc mode when the link between the BS and a node fails. A route is discovered by monitoring neighbor's communication, instead of broadcasting a route request packet. The network employs a dedicated MAC protocol based on Time Division Multiplexing (TDM). It takes the advantage of TDM based MAC to reduce delay; but suffers from lower network throughput.

A network architecture for disaster recovery is presented in [102]. This architecture has the following properties: (*i*) ability to co-exists, both in ad hoc as well as other infrastructure based networks, and (*ii*) easy to deploy and maintain. Authors in this paper have modeled the survivors movement as a two-dimensional random walk, and they introduced a concept called *reward-based random walk*.

An emergency response framework to achieve reliable communication in a dynamic wireless environment is discussed in [109]. The framework elaborates the link characteristics and connectivity properties in different mobility scenarios.

A mobility model for emergency response is proposed in [105]. The model supports heterogeneous area-based movement on an optimal path with the provision for nodes to join or leave.

5.3 Proposed Framework

When a disaster strikes, the number of persons seeking disaster information grows significantly. This may lead to congestion in the network, as a result end-to-end delay increases and degrades the network throughput drastically. Majority of the routing protocol selects the minimum-hop path between the source-destination pair in routing traffic. Reuse of the same path over and over again, will lead to quicker depletion of battery power at the nodes on the path. Moreover, shortest path routing does not achieve load balancing in the network. A path break leads to loss of data and the reconfiguration of network takes longer time. A node transmitting with maximum power is likely to deplete its battery power quickly. As battery power is an important resource for the longevity of the network, it must be judiciously used to increase the network lifetime [2, 110]. To overcome the above identified problem in an ad hoc network deployed for disaster response, we proposed the following:

(*i*) A multi-channel MAC protocol to mitigate the likely-hood of congestion in a disaster environment, and to achieve higher throughput and minimal delay.

(*ii*) A multi-path routing to overcome the problem associated with minimum-hop routing, and to provide reliable communication. Moreover, load balancing can be achieved through multi-path routing.

(*iii*) A topology management scheme to minimize the maximum transmission power of a node.

We explain the above proposals in the following sub-sections.

5.3.1 Multi-channel MAC

Using a multi-channel media access control protocol, different devices can transmit in parallel, on distinct channels. The parallelism increases the throughput and can potentially reduce the delay. Protocols differ in how devices agree on the channel to be used for transmission and how they resolve potential contention for a channel. There are many variations on multi-channel protocols. Based on the principle of operation multi-channel MAC can be categorized into (i) common hopping, (ii) split phase, and (iii) dedicated control channel [111]. Both common hopping and split phase based approach nodes have only one radio. In common hopping approach a pair of nodes stop hopping as soon as they make an agreement for transmission and rejoin the common hopping pattern subsequently after transmission ends. Examples of this approach include channel hopping multiple access with packet trains [112] and channel hoping multiple access [113]. In split phase approach, time is divided into an alternating sequence of control and data exchange phase. During a control phase, all devices tune to the control channel and attempt to make agreements for channels to be used during the data exchange phase. Multi-channel access protocol [114] is based on split phase based approach. In dedicated control channel based approach each node has two radios. One radio is used to exclusively for transmitting control messages and the other radio can tune to any other channel. In principle, all devices can overhear all the agreements made by other devices, even during data exchange. Dynamic private channel [115] is based on dedicated control channel approach. Our proposed multi-channel MAC protocol uses two radio similar to dedicated control channel based approach and is discussed below.

In the proposed multi-channel MAC (MMAC) protocol available channel is divided into two types: (*i*) Control channel, and (*ii*) Data channel. There is a single control channel that carries the control information, while the rests are data channel that carries data packets. Control channel is continuously monitored. Each node is equipped with dual transceiver; one for control and the other for data. Since, there is a separation between control channel and data channel, transmission of control and data packet at a node can overlap. Exposed and hidden terminal problems are inherent in ad hoc networks. Presence of hidden and exposed terminals degrades the system throughput [37–39]. An attempt is made in the proposed MMAC to minimize the impact of exposed and hidden terminals on network throughput. The working of the proposed MMAC is described below:

1. Each node maintains two tables: (*i*) *Transceiver Status Table*: Indicates the status of the radio transceiver of data channel of its neighboring nodes, and (*ii*) *Channel Status Table*: Indicates the status of each data channel. The structure of transceiver status table and channel status table are shown in Table 5.1 and Table 5.2 respectively.

Table 5.1: Structure of the transceiver status table

Node ID	Transceiver Status	Duration
M	Busy	t1
N	Free	-

Table 5.2: Structure of channel status table

Channel #	Status	Duration
Ch_1	Busy	t1
Ch_2	Free	-

Transceiver of a node as well as the data channels can be in one of the following two states: (*i*) $Free$, and (*ii*) *Busy*. The *Transceiver Status Table* and *Channel Status Table* are updated when a node receives a request-to-send (RTS), clear-to-send (CTS) or an acknowledgment (ACK1) packet. Initially, status of the transceiver of all nodes as well as data channels are set to $Free$. Data transmission takes place through the exchange of RTS-CTS-ACK1-DATA-ACK2 packet. A node having data packet, transmits a RTS packet which includes the identity of all channels, whose status is set to *Free*.

2. Neighboring nodes of the source other than the destination on hearing the RTS packet, runs a timer. These nodes expect an ACK1 from the source. A node on receiving either ACK1 from the source before the timer expires or CTS from the destination updates its status table.

3. Destination on receiving the RTS packet does the following: (*i*) Selects a channel based on the information available in its *Channel Status* table, and channel request made in the RTS packet, (*ii*) Sets the status of source node transceiver to *Busy* for the duration of data transmission, (*iii*) Transmits a CTS packet in response to RTS packet which includes the channel selected for communication, and (*iv*) Sets the status of the selected channel to *Busy* for the duration of transmission. If the destination could not reserve a channel then it transmits a NACK message. The source on receiving NACK message waits for a random period of time, then re-transmit the RTS packet.

4. Nodes, including the source on receiving CTS packet update their status table as follows: (*i*) Set the status of destination node transceiver to *Busy* for the duration of data transmission, (*ii*) Set the channel reserved for data transmission to *Busy* for the period of data transmission.

5. Source performs the following activities after updating its status table: (*i*) Transmit an ACK1 packet, containing the channel identity reserved for data transmission, and (*ii*) Transmit the data packet after a random period of time.

The proposed MMAC, also attempts to minimize the impact of hidden terminal and exposed terminal problem. The hidden nodes and/or exposed nodes can transmit or receive on any data channel that is set to *Free*. A data packet is transmitted only after a data channel is reserved. This, ensures that data collision does not take place. However, the collision of control packets may take place.

Operation of the proposed MMAC scheme is illustrated through Figures 5.1, 5.2 and 5.3. Channel status table and transceiver status table at each node is shown in the above Figures. We have assumed that there are three data channels, all set to *Free* initially. Initial configuration of channel status table and transceiver status table is shown in Figure 5.1.

Suppose node **B** has a data destined to node **C**. Then the source node **B** transmit a RTS to destination node **C**. This is shown in Figure 5.1. This RTS packet includes the free channels, *viz.* Ch_1, Ch_2, Ch_3 marked as *Free* in the channel status table

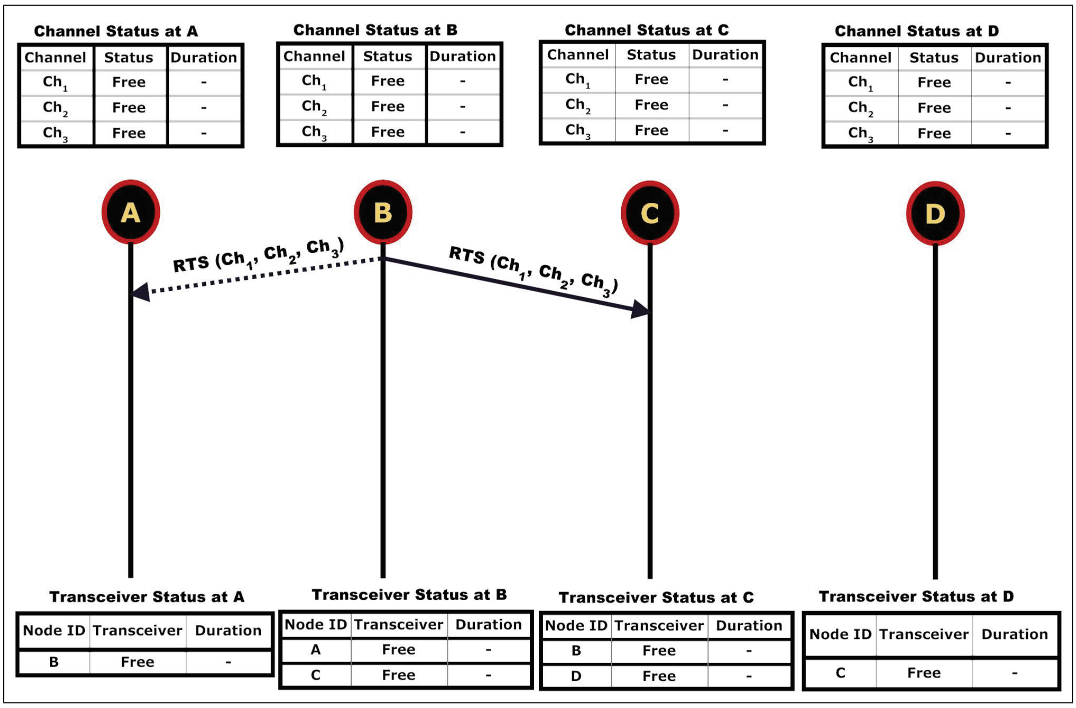


Figure 5.1: Initial configuration of the channel status table and transceiver status table.

of node **B**. Destination node **C** selects a channel depending on the status of the channels in its channel status table and the channel request made by source **B** in the RTS packet. Let node **C** selects channel Ch_1. Then, it prepares a CTS packet and transmit to source node **B** as shown in Figure 5.2.

Neighbor of node **C** *i.e*, node **D** on hearing the CTS packet, update its status table. The updated transceiver status table is shown in Figure 5.2. The source node **B** on receiving CTS packet from the destination, update its status table and transmit an ACK1 packet containing the channel ID *i.e*, Ch_1 selected for data transmission and the duration of data transmission. Neighboring nodes of **B** other than the destination **C** on receiving ACK1 packet update their status table. Source **B** then transmits the data packet.

Neighboring nodes of the source **B** in their status table, set the status of source node transceiver and the selected channel to *Busy*. Similarly, the neighboring nodes of the destination **B**, in their status table, set the status of the destination node transceiver and the selected channel to *Busy*.

Hidden nodes and exposed nodes can transmit and/or receive in a separate channel which can overlap with the on-going transmission. For example, the hidden

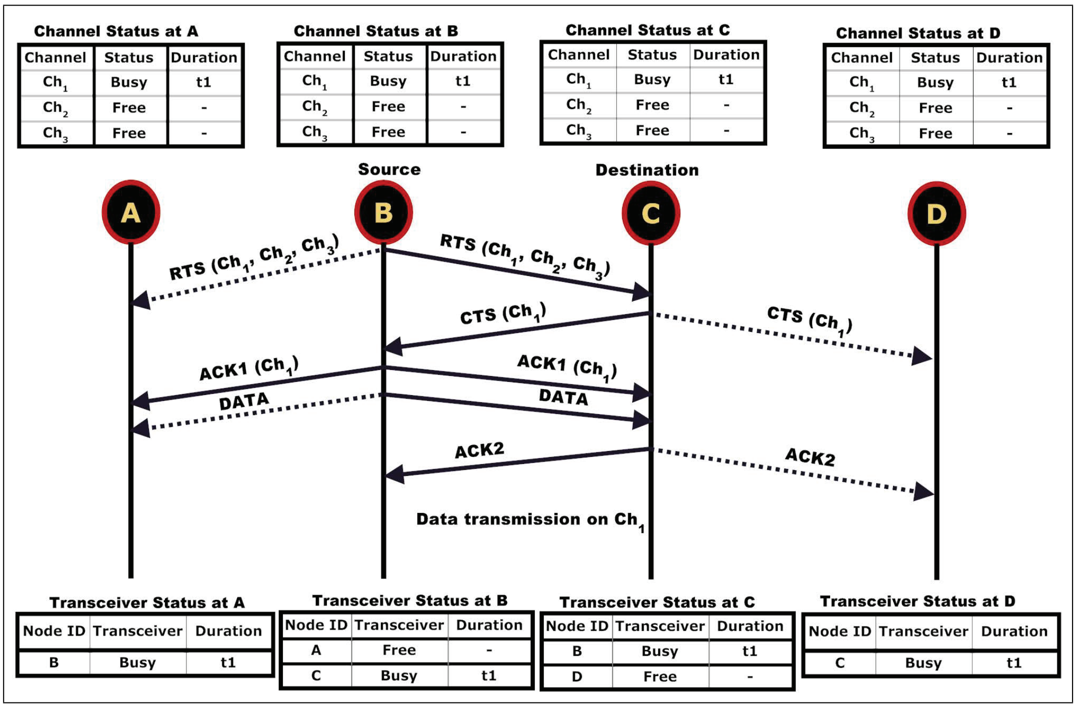


Figure 5.2: Transceiver status and channel status during data transmission.

node **D** can overlap its own transmission with the on-going transmission. This is shown in Figure 5.3. In this Figure the hidden node **D** is transmitting to node **E**. We have assumed that, the status of all channels is set to $Free$ in the status table at node **E**.

Advantages of the proposed MMAC scheme are: (i) Hidden nodes and exposed nodes can transmit simultaneously in separate distinct channel; this contributes to the increases in network throughput, (ii) End-to-end delay is reduced, this is because the waiting time of packets at a node is reduced due to the availability of multiple data channels, and (iii) Energy efficiency is achieved by minimizing congestion.

5.3.2 Energy aware disjoint multipath routing

Routing protocols based on hop count metrics are not suitable for disaster environment; as hop count is not sufficient enough to determine the quality and stability of a path. Protocols based on hop count metric suffer from lower throughput and higher end-to-end delay. They are also affected by higher link failures and lower energy efficiency in a heavily congested network such as in a disaster environment. Energy efficiency is a crucial design criteria to enhance the network lifetime. If a

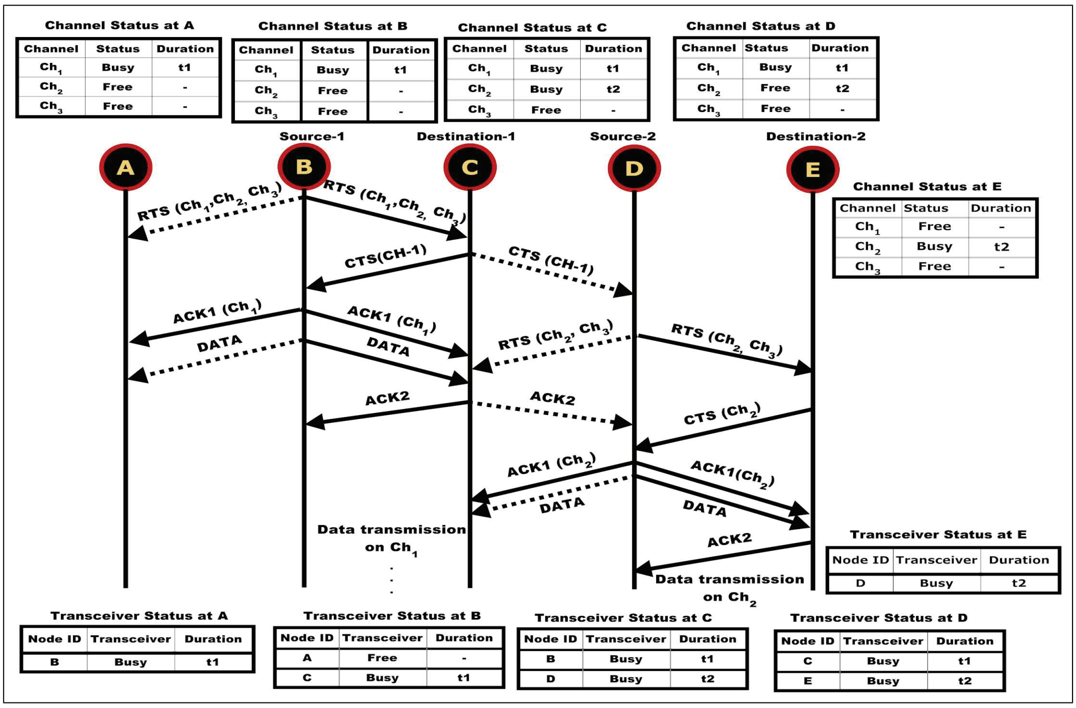


Figure 5.3: Transmission from exposed node, overlapping with on-going transmission.

node dies due to lack of battery power, then the network connectivity is lost, which not only affects the network lifetime but also the network throughput adversely. Therefore, a robust routing mechanism is required to overcome the above issues. In this sub-section, we propose a routing protocol which selects k node-disjoint path between a source-destination pair based on their lifetime. Traffic between the source-destination pair is routed through k-alternate paths in order to achieve load balancing in the network. Moreover, disjoint paths can provide an alternate path against link failures. Computation of node-disjoint paths is explained below:

Route discovery:

1. Source node initiates a *route discovery process*, by broadcasting a route request (RREQ) packet. The RREQ packet carries lifetime of the sender along with other information such as: *message sequence number, source ID, destination ID*, etc. The RREQ also carries the path information between a source-destination pair. A node calculates its lifetime as explained in Chapter 3, Section 3.2.1.

2. An intermediate node on receiving the RREQ packet computes its lifetime. Then, the node updates the lifetime field in the RREQ packet if the computed lifetime is less than the value in the lifetime field of the received RREQ packet. Duplicate RREQ packets for the same source-destination pair are dropped at each intermediate node. The above process is continued until the RREQ packet reaches the destination.

Route selection:

1. Destination on receiving the first RREQ packet between a source-destination pair starts a timer. At the expiry of the timer, it executes a *path selection procedure* to find the k node-disjoint paths. Subsequent RREQ packets received after the expiry of the timer are not considered for path selection. A destination may receive more than one RREQ packet at the expiry of the timer. The *path selection procedure*, first rearranges the RREQ packets in the decreasing value of lifetime. Then, it selects the k node-disjoint paths between the source-destination pair. A path having higher lifetime is more energy efficient.

2. After selecting k node-disjoint path, destination prepares the route reply packet (RREP). The RREP packet includes current location information of forwarding node, and is forwarded to next-hop node on the path to the source.

3. Each next-hop node on receiving the RREP packet update its routing table. A typical structure of routing table is shown in Table 5.3. Location information of the node, that has forwarded the RREP packet is recorded in the location field of the routing table. *RREP Receiving time* records the time at which the node has received the RREP packet. This process continues until RREP packet reaches the source. Each intermediate node update the current location field of the RREP packet before forwarding.

Table 5.3: Structure of routing table

Source	Destination	Next-Hop Address	Location	RREP Receiving Time
S	D	K	(x_1, y_1)	t_1

4. Source on receiving the RREP packets, update its routing table. Then, it determines the transmission power required to send data packet to the next-

hop node on the path, and start transmitting data. The k node-disjoint paths are used to transmit data between the source-destination pair.

Route maintenance:

In the proposed scheme route maintenance is triggered only when all the paths between source-destination pair fails. We have assumed that the MAC layer is able to notify the network layer in case of path failure. The source node then responds simply by not sending data through the broken path. In the proposed scheme route discovery due to path failure is initiated only when all the k node-disjoint paths between a source-destination pair fails.

Working procedure of the proposed disjoint path routing is illustrated in Figure 5.4 and Figure 5.5. Source node **S** initiates the route discovery process. Figure 5.4 shows the route discovery process. Destination node **D** selects two node-disjoint paths **S-A-E-D** and **S-B-C-F-D** based on their lifetime. Figure 5.5 shows the propagation of RREP from destination **D** to source **S** through path **S-A-E-D** and **S-B-C-F-D**. Updation of routing table, and RREP from each node is also shown in Figure 5.5. Routing table at source **S**, after receiving two RREP packets from destination **D** is shown in Table 5.4.

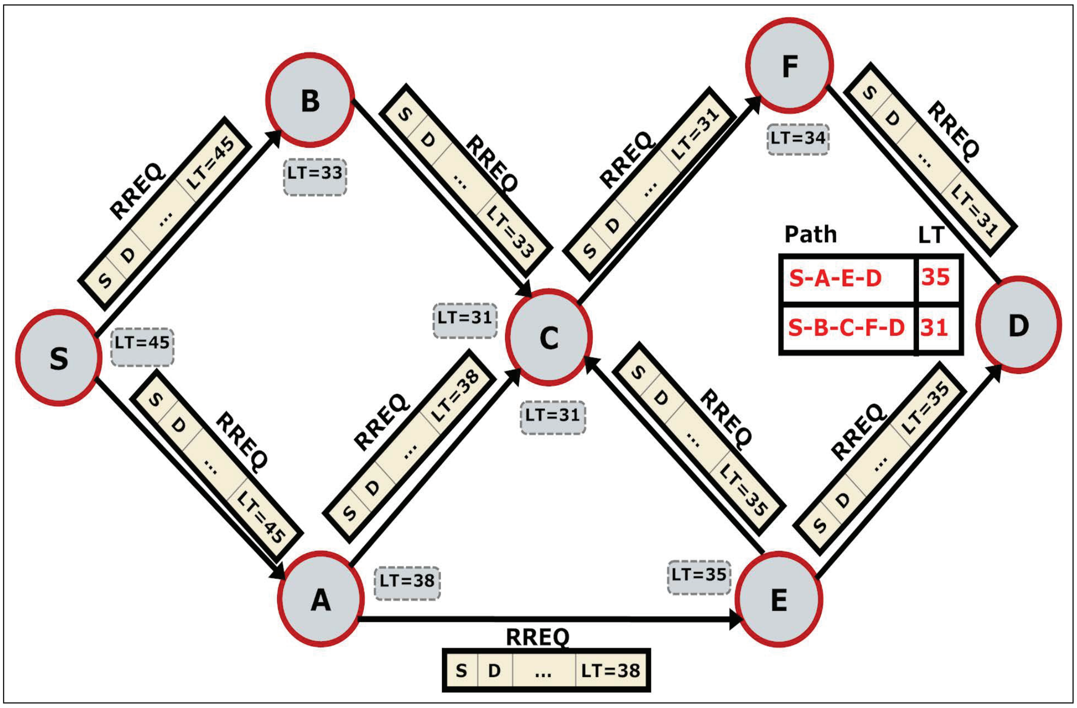


Figure 5.4: Transmission of RREQ from source **S**.

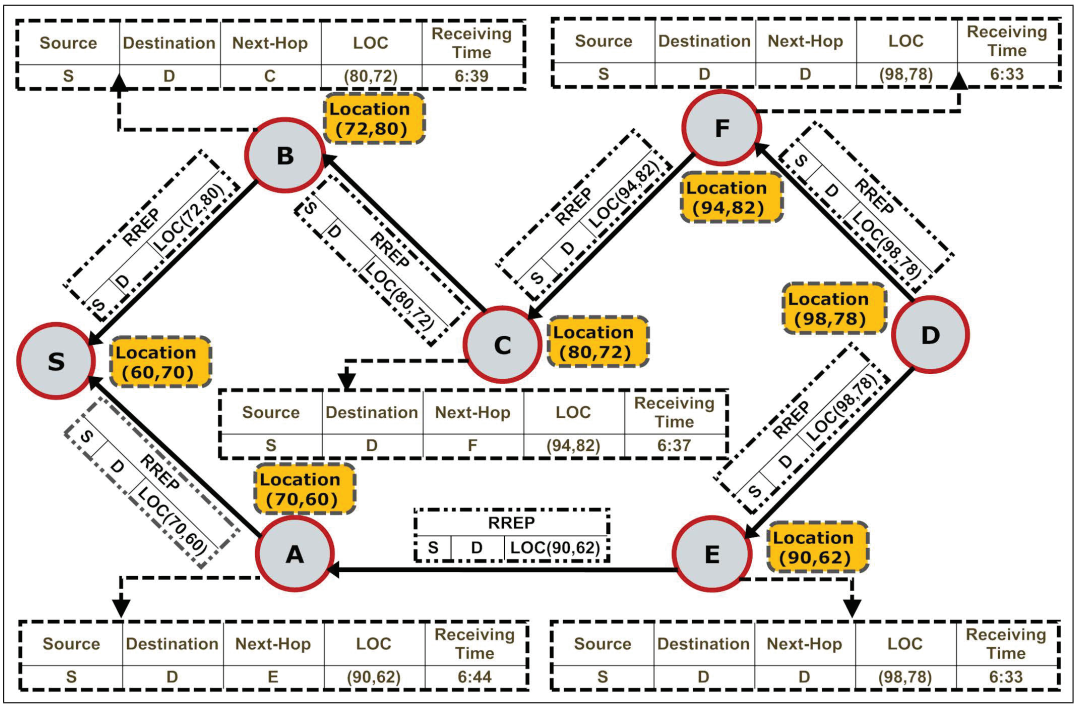


Figure 5.5: Multi-path disjoint route reply from destination **D**.

Table 5.4: Source node **S** routing table

Source	Destination	Next-Hop Address	Location	RREP Receiving Time
S	D	A	(70, 60)	6 : 41
S	D	B	(72,80)	6 : 42

Advantages of the above proposed routing scheme are: (*i*) Path is selected based on energy consumption rate and residual battery power. This improves energy efficiency, and network lifetime, (*ii*) Load balancing is achieved, and (*iii*) Delay and congestion can be reduced. A source selects one of the k-disjoint path, for one session of data transfer, and another path for the next session. Since no particular path is overutilized the longevity of nodes are enhanced.

5.3.3 Topology management

Interference is an indirect source of energy waste. Collision due to interference leads to retransmission. Each retransmission depletes the energy level of a node. Also degrades the network throughput.

Control packets such as RTS, CTS, ACK, NACK are usually transmitted at maximum power. Transmitting at maximum power causes more interference in the network. To reduce the level of interference, hence, the energy depletion at a node, control packets must be transmitted at a reduced power level without loosing the network connectivity.

In this section we proposed a mechanism based on topology control to determine the maximum reduced transmission power level at a node. Working procedure of the proposed topology management scheme is described below.

1. A node periodically broadcasts a *Hello* message which contains sender ID and its location information, with maximum power.

2. A node on receiving the *Hello* message updates its *vicinity* table, which is maintained at each node. The structure of the vicinity table is shown in Table 5.5.

   Table 5.5: Structure of Vicinity Table

Sender ID	**Location Information**	**Computed Power**	**Common Node**	**Minimum Power**
S	(x1,y1)	P	-	P

   The purpose of each field in the vicinity table is explained below: *Sender ID* field records the *ID* of the sender of the *Hello* message, location information of the sender is recorded in *Location Information* field, *Computed Power* field records the transmission power required to communicate with the sender; which is computed as: P = D^{β} $+C$, where D is the Euclidean distance between the node and sender of the *Hello* message, β is the path loss exponent, where $2 \leq \beta \leq 4$, and C is a constant. *Common Node* field records the common node between the node and sender. Common nodes are those nodes , through which if transmitted, the power expended by the node will be lower. Initially, the value in the *Minimum Power* field is same as that of the *Computed Power* field, it is updated when there exist a common node between receiver and sender. For example, suppose there exists a node i between u and v, such that: $P_{ui} + P_{iv} < P_{uv}$. where P_{ui}, P_{iv} and P_{uv} are the computed power between $u \rightarrow i$, $i \rightarrow v$ and $u \rightarrow v$ respectively, then node u, sets the *Minimum Power* for node v to P_{ui}.

3. After updating the vicinity table, a node determines its transmission power

which is maximum of the value in the *Minimum power* field.

The proposed topology management is illustrated in Figure 5.6. We have considered node **A** for our illustration. Node A after receiving *Hello* message from its neighbors, updates its vicinity table. Updated vicinity table at node A is shown in Table 5.6.

Table 5.6: Node **A** Vicinity Table

Sender ID	**Location Information**	**Computed Power**	**Common Node**	**Minimum Power**
B	(24,27)	30	-	30
C	(18,25)	26	-	26
D	(15,15)	99	E	54
E	(20,15)	54	-	54
F	(28,22)	37	-	37

Then, node **A** determines its transmission power which is maximum of the value in the *Minimum Power* field. Transmitted power computed by node **A** is *max (30, 26, 54, 54, 37) = 54*.

Advantages of the above proposed topology control mechanism is: (*i*) Minimizes interference in the network, and (*ii*) Save energy at each node by reducing the transmission power.

In the proposed disaster management framework, a node first determines its maximum transmission power as discussed in Section 5.3.3. Then, the k node-disjoint path between the node itself and destination is determined as specified in Section 5.3.2, and finally data transmission takes through the multi-channel MAC as explained in Section 5.3.1.

5.4 Simulation Results

In this section, first we evaluate the performance of the proposed disaster management framework using *QualNet 4.5* simulator [69] varying the traffic and node mobility. Parameters considered for the simulation is mentioned in Table 5.7. The following metrics are considered for evaluation: *Energy consumption*, *Network lifetime*, *Throughput*, and *End-to-end delay*.

A: Energy consumption

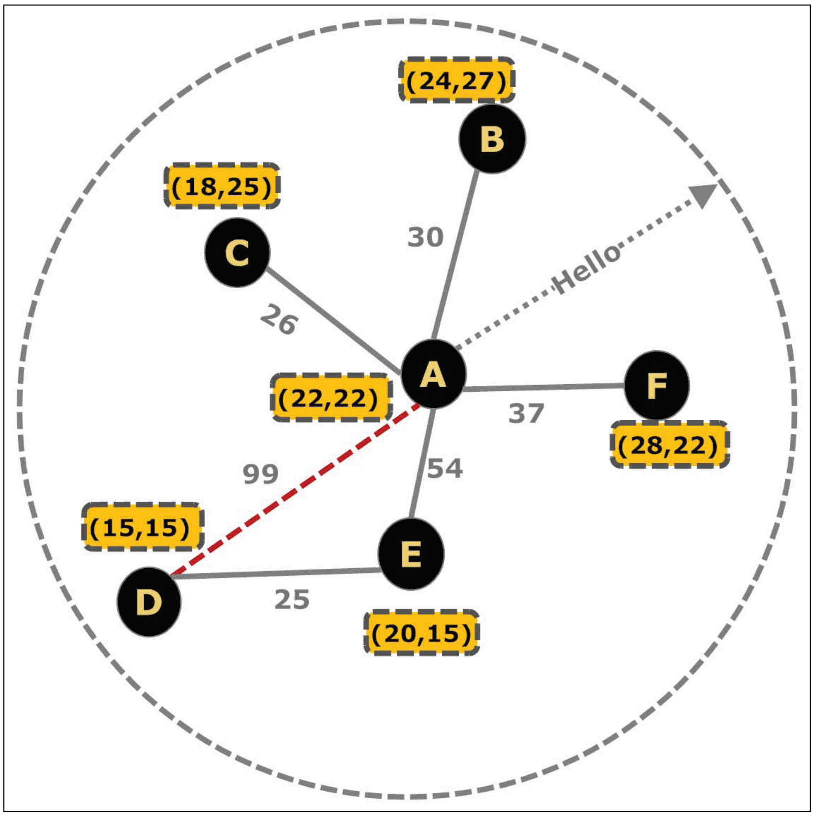


Figure 5.6: Computation of transmission power at node **A**.

Plots for energy consumption *vs.* CBR connection, and pause time are shown in Figures 5.7 and 5.8 respectively. It is observed from Figure 5.7 and 5.8 that the energy consumption decreases with increase in channel. This is because, as the number of channel increases, the contention for the channel decreases. As a result the number of retransmission decreases. This contributes to the decrease in energy consumption.

B: Network lifetime

We defined the lifetime as the duration of network operation until the first node fails due to battery depletion at the node. The plot for network lifetime *vs.* CBR connection, and pause time is shown in the Figure 5.9 and 5.10 respectively. It is observed from the above Figures that the network lifetime is enhanced with increase in the number of channels. This is because, the energy consumption decreases with increase in the number of channels.

C: Throughput

Table 5.7: Simulation Parameters

Simulation Time	120 Minutes
Terrain-Dimension	1500 * 1500 m^2
Number of nodes	100
Traffic type	CBR
Mobility model	Random Waypoint
Maximum node speed	10 m/s
Pause time	0 - 500 second
Pathloss model	Irregular terrain model
Radio Type	802.11b
Propagation limit	-111 dBm
Initial battery capacity	300 mAh
k	2

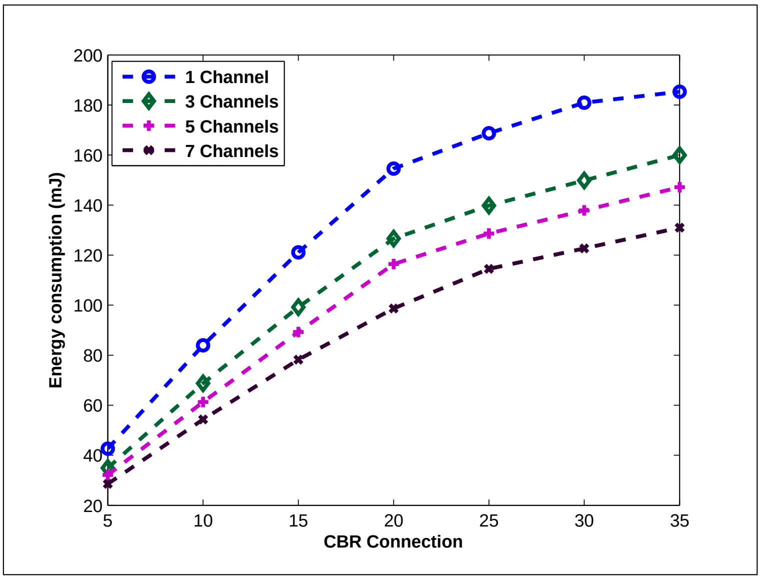


Figure 5.7: Energy consumption *vs.* CBR connection at 50 pause time.

We plot the throughput *vs.* CBR connection, and pause time in Figure 5.11 and 5.12 respectively. From Figure 5.11, it is observed that, for a given CBR connection, a network with more numbers of channel have higher throughput. With increase in the number of channels, congestion in the network decreases for a given

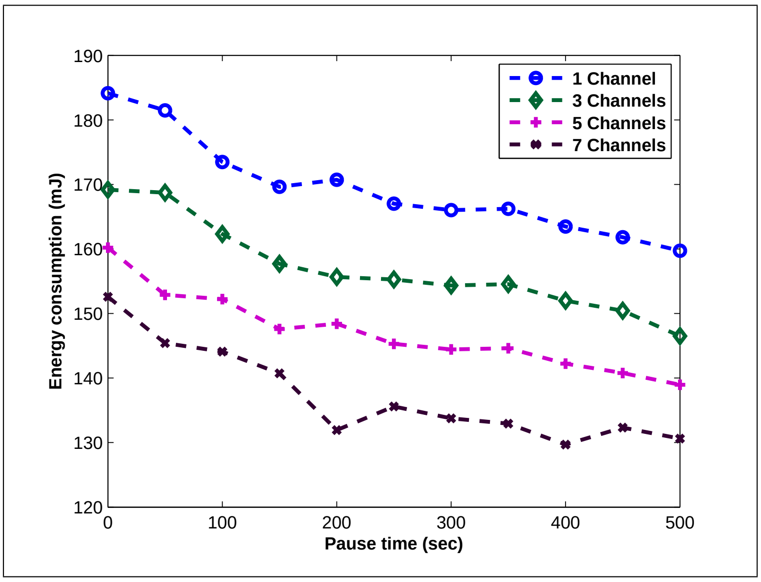


Figure 5.8: Energy consumption *vs.* Pause time at 30 CBR connection.

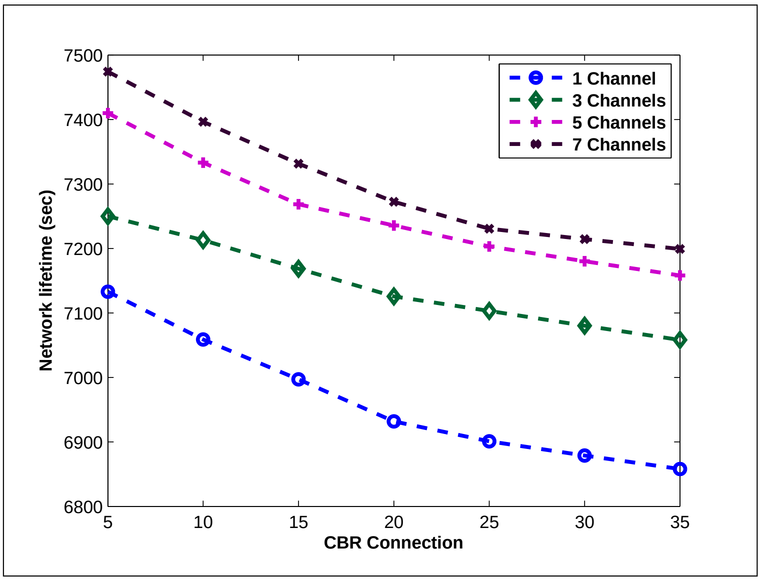


Figure 5.9: Network lifetime *vs.* CBR connection at 50 pause time.

number of connections. As a result, network throughput increases. Moreover, with the availability of more number of channels transmission from hidden and exposed nodes contribute to the increase in throughput. It is also observed from Figure 5.12 that for a given pause time, network with more numbers of channel has higher throughput. The reason for this is also same as stated above.

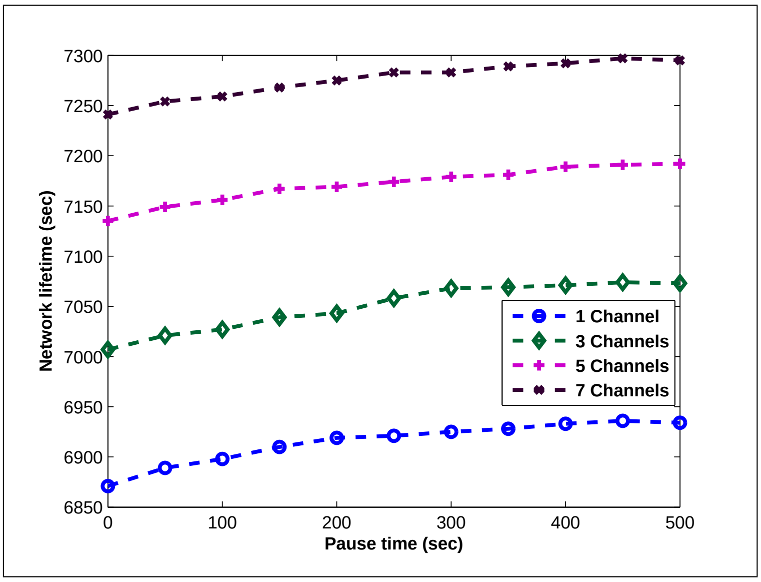


Figure 5.10: Network lifetime *vs.* Pause time at 30 CBR connection.

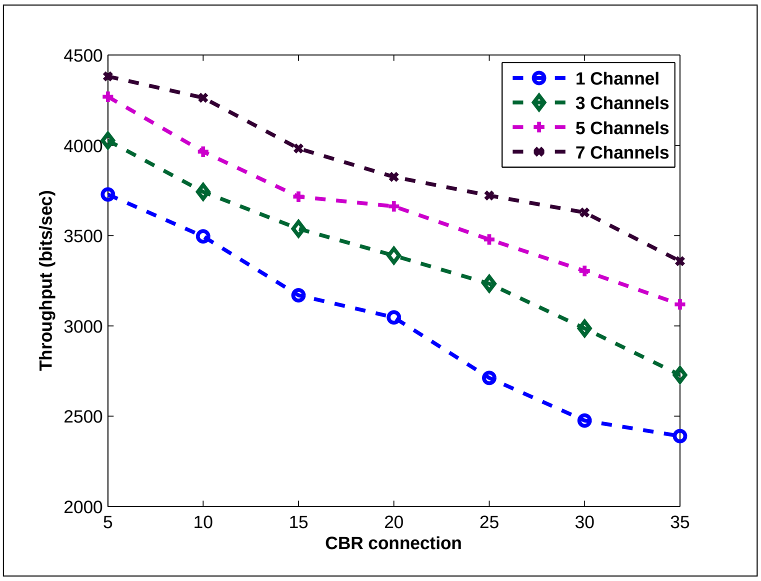


Figure 5.11: Throughput *vs.* CBR connection at 50 pause time.

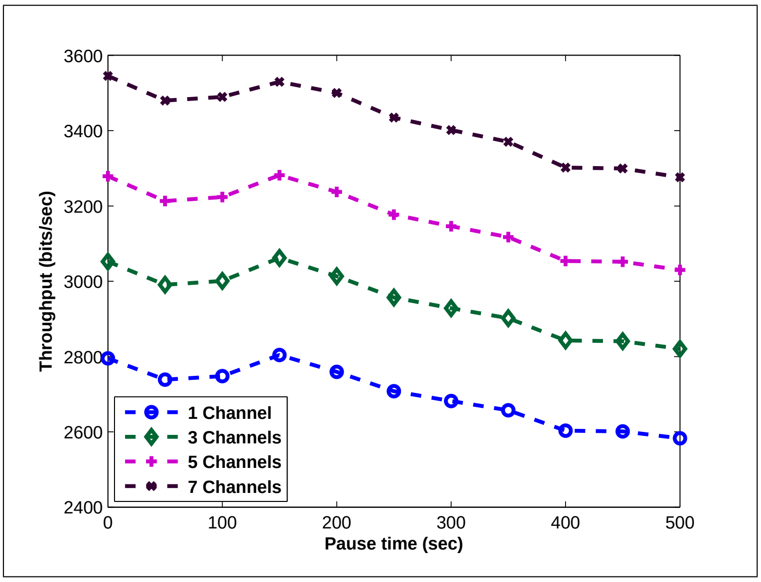


Figure 5.12: Throughput *vs.* Pause time at 30 CBR connection.

D: End-to-end delay

Plot for end-to-end delay *vs.* CBR connection, and pause time is shown in Figures 5.13 and 5.14 respectively. It is observed from the above Figures that the end-to-end delay decreases with increase in number of channels. Lower end-to-end delay is partly attributed to decrease in congestion and partly due to transmission from hidden and exposed nodes.

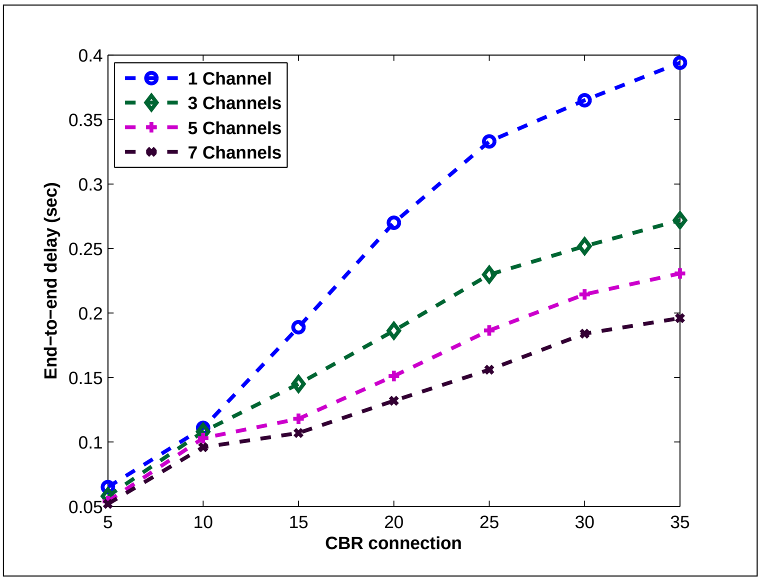


Figure 5.13: End-to-end delay *vs.* CBR connection at 50 pause time.

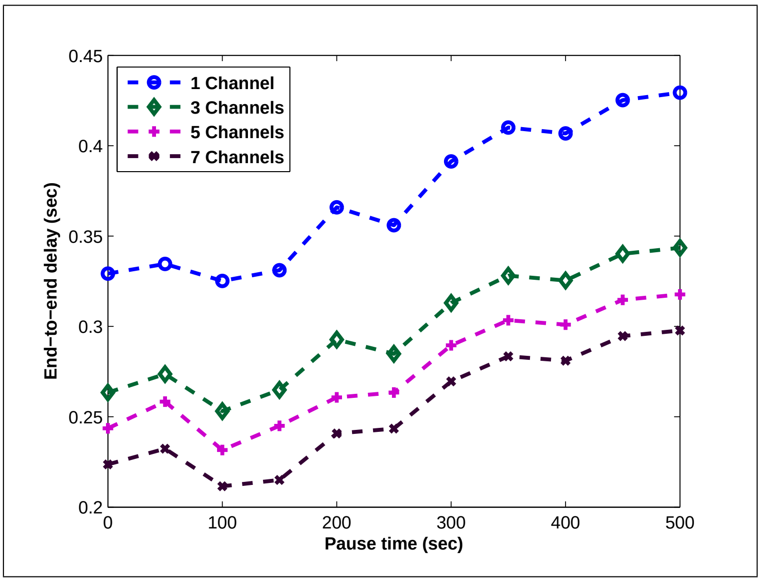


Figure 5.14: End-to-end delay *vs.* Pause time at 30 CBR connection.

Next, we compared the proposed disaster management framework with *Distressnet* [25]. Metrics considered for comparison are *Energy consumption, Network lifetime, Throughput* and *End-to-end delay.*

E: Comparison for Energy consumption

The plots for energy consumption *vs.* CBR connection, and pause time is shown in Figures 5.15 and 5.16 respectively. It is observed from the above Figures that the proposed scheme has lower overall energy consumption as compared to *Distressnet.* The lower energy consumption is attributed to energy aware path selection, use of variable transmission power, and the techniques employed for minimizing interference and congestion in the network.

F: Comparison for Network lifetime

The plot for network lifetime *vs.* CBR connection, and pause time is shown in Figure 5.17 and 5.18 respectively. From the above Figures it is observed that the proposed mechanism has higher network lifetime compared to *Distressnet.* This is because of the lower energy consumption in the proposed scheme. Transmission through k node disjoint paths also contributed to the increase in network lifetime.

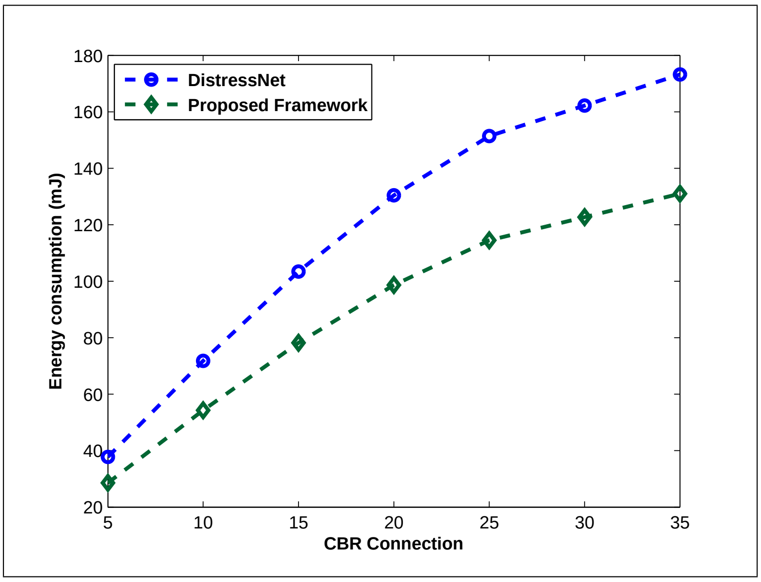


Figure 5.15: Comparison of Energy consumption *vs.* CBR connection at 50 pause time.

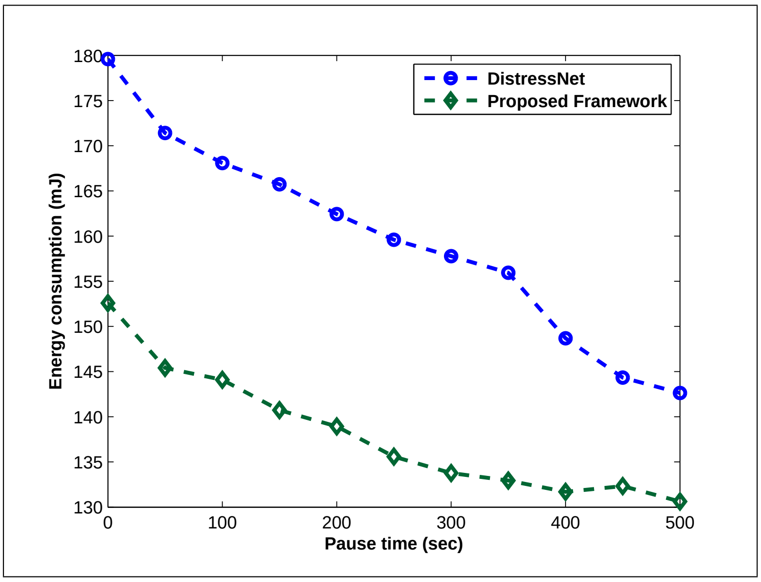


Figure 5.16: Comparison of Energy consumption *vs.* Pause time at 30 CBR connection.

G: Comparison for Throughput

The plots for throughput *vs.* CBR connection, and pause time is shown in Figure 5.19 and 5.20 respectively. It is observed from the above Figures that proposed scheme has higher throughput compared to *Distressnet*. Higher throughput is at-

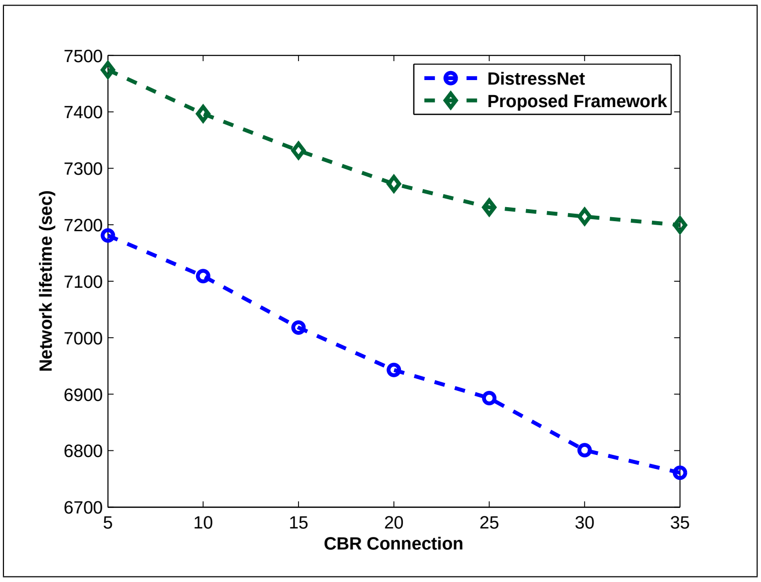


Figure 5.17: Comparison of Network lifetime *vs.* CBR connection at 50 pause time.

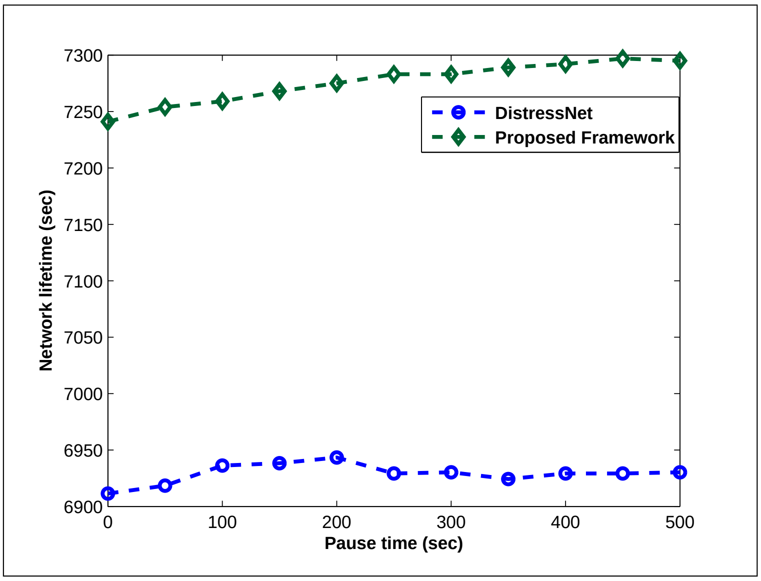


Figure 5.18: Comparison of Network lifetime *vs.* Pause time at 30 CBR connection.

tributed to enhancement in the network lifetime. Transmission from hidden and exposed nodes, also contributed to the increase in throughput.

H: Comparison for End-to-end delay

The plot for end-to-end delay *vs.* CBR connections is shown in Figure 5.21. It is observed from the Figure that end-to-end delay increases with increase in the

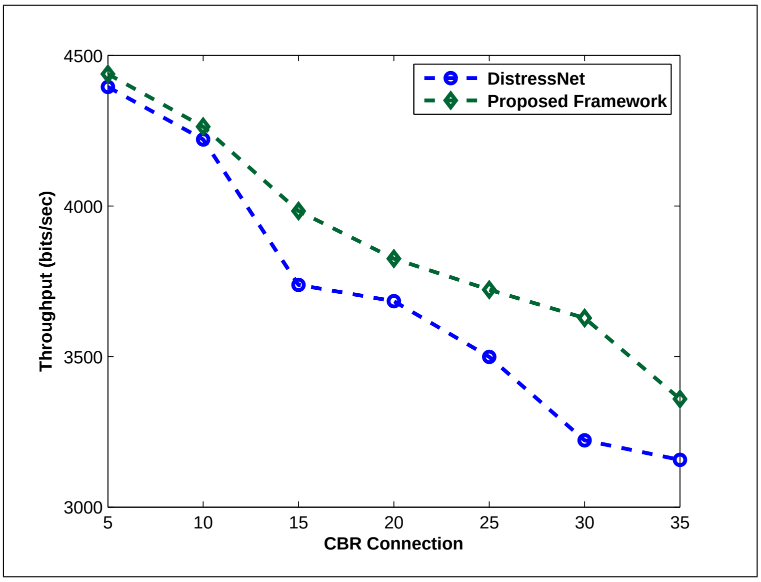


Figure 5.19: Comparison of Throughput *vs.* CBR connection at 50 pause time.

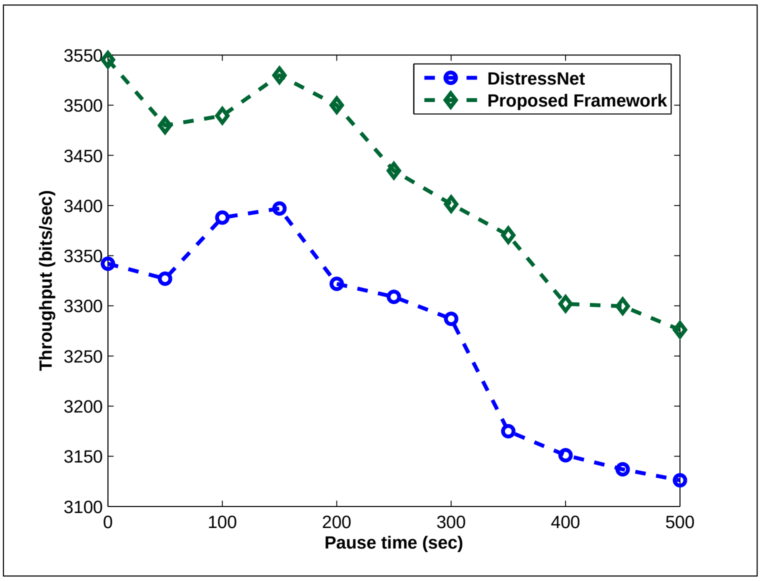


Figure 5.20: Comparison of Throughput *vs.* Pause time at 30 CBR connection.

number of CBR connections. This is consistent with the published result [116]. Figure 5.22 shows the plot for end-to-end delay *vs.* pause time. It is observed that the proposed framework has lower end-to-end delay compared to *Distressnet*. The lower end-to-end delay is attributed to the multiple data channel, simultaneous transmission/reception from hidden and exposed nodes.

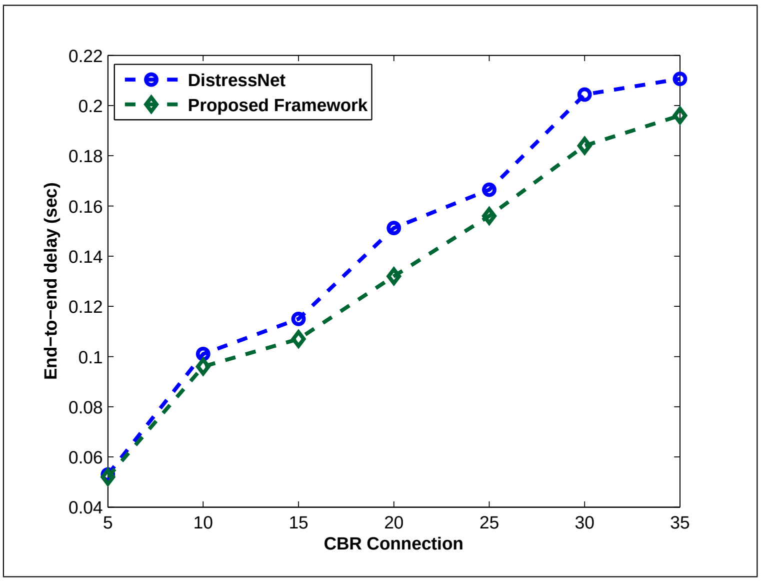


Figure 5.21: Comparison of End-to-end delay *vs.* CBR connection at 50 pause time.

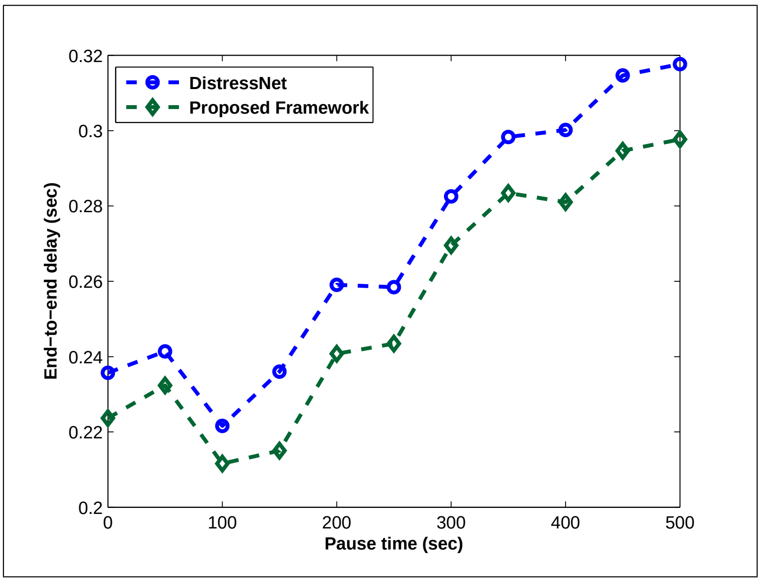


Figure 5.22: Comparison of End-to-end delay *vs.* Pause time at 30 CBR connection.

5.5 Summary

In this chapter, we proposed a framework for post-disaster communication using wireless ad hoc network. The proposed framework attempts to: (*i*) maximize network throughput, (*ii*) minimize the average end-to-end delay, and (*iii*) improve the network lifetime. The available channels are split into control and data channel. There is one dedicated control channel. Each node is equipped with dual transceiver, one for control and the other for data. A reservation mechanism is employed for data transmission. A multi-channel MAC protocol is proposed to improve network throughput. It also achieves energy efficiency by minimizing congestion. Load balancing is achieved by transmitting the traffic through more than one-path. A topology management scheme is applied to minimize the maximum transmission power of a node. All these mechanisms combined to support a situational awareness suitable for mission critical decision system. The proposed framework is compared with *Distressnet*. We observed that the proposed framework outperforms *Distressnet* in term of throughput, end-to-end delay and network lifetime. Moreover, the model can be applicable for other applications, where throughput, delay, and energy efficiency are considered as an important quality of service (QoS) parameters as perceived by the end users.

In the next chapter, we made a few conclusions, and highlight the major contribution of the thesis.

Chapter 6

Conclusions

The work presented in this thesis is guided by the need for energy efficiency in MANETs. We have considered an ad hoc network which is likely to become a de-facto standard for infrastructure-less wireless network. We have proposed a few techniques for power saving in MANET. First, we proposed a routing technique to minimize the energy consumption at network level. Then, we use the topology control and power management approach to save energy at node level. We have also proposed a framework to support communication among the mobile nodes in a disaster environment. The work presented in this thesis is a step towards energy efficiency in MANETs. In the remainder of this chapter, we briefly summarize the original contributions of our study. Finally, some suggestions for future work are given.

6.1 Contributions

6.1.1 Routing technique

We proposed, a routing technique to enhance the lifetime of MANET. The routing technique considers the following in selecting a path: (*i*) node lifetime, (*ii*) node transmission power, and (*iii*) node utilization. A cost metric to compute the nodes lifetime is proposed. It considers the nodes residual battery power and energy consumption rate. Node uses variable transmission power for data packet. Transmission power is computed, based on the location of the next-hop node. To minimize the overutilization of node, a maximum limit on the number of paths that can be established to each destination is set. Through simulation, we have shown that the proposed technique is energy efficient and improves the network lifetime.

6.1.2 Hybrid energy saving technique

An energy conservation technique called *Location Based Topology Control with Sleep Scheduling* (LBTC) is proposed for ad hoc networks. The merits of both topology control approach and power management approach is considered in LBTC. Like the topology control approach, it attempts to reduce the transmission power of a node. A node goes to sleep state based on its traffic condition similar to power management approach. LBTC operates in two phases: (*i*) *link selection* phase, and (*ii*) *sleep scheduling* phase. In link selection phase a node determines its transmission power. In the sleep scheduling phase a node determines whether it can go to sleep state. A node goes to sleep state only when the following conditions are satisfied: (*i*) it has no traffic, and (*ii*) its absence does not create a local partition. We have compared LBTC with two existing schemes. It is observed that LBTC is more energy efficient and have longer network lifetime.

6.1.3 Framework for post-disaster communication

In our previous two schemes, network lifetime is enhanced at the expense of higher end-to-end delay. However, in some applications such as in emergency response system above two parameters are equally important. Keeping disaster in mind, a framework is proposed for post-disaster communication to enhance the network lifetime as well as reduce the end-to-end delay. The proposed framework includes: (*i*) a multi-channel MAC protocol, (*ii*) an energy aware multi-path routing, and (*iii*) a distributed topology aware scheme. Above proposals, taken together intend to increase the network lifetime and throughput, and reduce the end-to-end delay. The proposed framework is compared with a closely related existing framework.

6.2 Future Research Directions

We briefly outline below the possible research directions.

Energy Aware Multicast Routing: Most of the research in MANET is focused on unicast. A very little work is done on multicast. Energy aware routing scheme can be extended to multicasting.

Cross Layer Designing: Cross layer design is another potential area of research. Information from different layer of MANET protocol stack can be considered to improve the overall performance in the networks. Cross layer design can also be used to conserve energy.

Security: For secured communication, some form of security mechanism must be built into the system. Since the nodes in MANET have low computation capabilities, the traditional public key cryptosystem can not be used. A light weight security mechanism, that requires less computation must be developed to provide security in MANETs.

Quality-of-Service: This is a level of service offered by the network to its user. The parameters of quality-of-service (QoS) is not properly defined for MANET. Some of the QoS parameters are delay, packet loss, reliability, throughput, etc. QoS parameters can be built into the routing mechanism in MANETs.

Energy harvesting: Energy harvesting is a promising approach to enhance the network lifetime. Nodes in MANET are powered by battery. It is difficult to replace or recharge battery in many situations. Solar power can be used to recharge the battery. This requires redesign of transceiver hardware.

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